An examination of the Geochemical properties of late devensian glacigenic sediments in Eastern England

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AN EXAMINATION OF THE GEOCHEMICAL PROPERTIES OF LATE DEVENSIAN GLACIGENIC SEDIMENTS IN EASTERN ENGLAND

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Abstract

Onshore advance of the North Sea lobe of the Late Devensian British Ice Sheet during the last glaciation resulted in the deposition of thick multiple till sequences along the coasts of east Yorkshire and north Lincolnshire. Despite an abundance of sedimentological and stratigraphical data, the origin of these tills remains controversial, and their correlation along the coast is poorly understood. These multiple till sequences provide an excellent opportunity to test models of large-scale subglacial sediment transport and deposition beneath soft-bed ice sheets using geochemistry. Such geochemical analysis has been used extensively in other formerly glaciated areas, notably Canada, to identify till characteristics and dispersal patterns. However, to date it has not been applied in any detail to glacial sediments in the UK and its potential as a tool for till correlation and understanding till genesis remains relatively undeveloped.

A detailed sampling method was employed at seven sites in eastern England; Filey, Skipsea, Dimlington, South Ferriby, Kirmington, Welton-Le-Wold and Morston; to investigate vertical and lateral changes in till geochemistry in this region. Particle size analysis of the till matrix was used as an additional tool to provide extra sedimentological data. Complete linkage and Ward's method cluster analysis was used to establish groups of geochemically similar diamicton samples.

Geochemical results suggest that there are vertical changes in till geochemistry, which are likely to be related to a change in provenance from local to more distal sources. Geochemistry and particle size results were also unable to precisely differentiate between the Basement, Skipsea and Withernsea till types. Instead, the repeated nature of the geochemical signature at larger sites, such as Dimlington, and the lateral discontinuity of some geochemical groups suggests that the till sequences at Filey, Dimlington, and Skipsea are comprised of a number of lithologically distinct rafts which have been tectonically stacked or elevated to higher levels in the sediment pile. At Dimlington the production of a glacitectonically folded and stacked moraine is proposed as a mechanism to explain the remarkably thick sequence of Withernsea Till and the repeated nature of the geochemical signature at this site. This research therefore provides new evidence for our understanding of glacial stratigraphy and former ice dynamics in eastern England, suggesting that till composition and the mechanics behind its production are more complex than the traditional stratigraphic division allows.

Contents

Figures

Chapter 5

Chapter 6

Appendix ii

Appendix iii

Tables

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Chapter 1: Introduction

1.1 Rationale

Until the 1980s glacier beds were assumed to be made up of rigid substrata, over which glaciers moved by ice flow or basal sliding. Since this time, it has been demonstrated that where a glacier is underlain by soft, unlithified sediments, a substantial amount of forward motion may be accounted for by the deformation of these sediments (Alley *et al.*, 1986; Boulton & Hindmarsh, 1987; Clarke, 1987; Alley *et al.*, 1987a,b; Alley, 1989a,b; Humphrey *et al.*, 1993). This coupling of the glacier and its bed has important implications for ice flow dynamics, the distribution of tills and the production of large-scale features such as drumlins (Boulton *et al.*, 2001). Understanding the patterns of erosion and deposition beneath ice sheets is therefore vital for increasing our knowledge of ice sheet dynamics as a whole.

Boulton (1996a,b) developed a theory to predict the pattern of sediment dispersal during a glacial cycle for such a soft bed ice sheet. Coupling of the ice-bed system results in a zonation where, in general, basal sediments are eroded in the proximal accumulation zone due to net acceleration, and these sediments are often deposited in the distal ablation area. As an ice sheet grows the zone of erosion also expands, causing the zone of deposition to be displaced progressively outwards and an 'advance-phase till' to be deposited. During retreat, a 'retreat-phase till' is deposited following the contraction of the depositional zone.

Boulton divided this spatial pattern into four zones, with the ice divide in Zone 1 and the most distal area, including the ice margin, as Zone 4. In Zone 3, towards the maximum of the zone of erosion, the length of time of the erosional phase is insufficient to completely remove the advance-phase till before a switch back to deposition during retreat. Thus, after deglaciation, a thick till sequence remains, which contains both advance- and retreat-phase tills separated by an erosional interface (Figures 1.1 & 1.3). Towards the terminus in Zone 4, erosion does not occur, and deposition is continuous. However, the rate of deposition varies, with the slowest during maximum ice sheet extent. Therefore a continuous thick sediment sequence is deposited in this zone (Boulton, 1996a). As a result, at an oscillating ice margin, this may result in the stacking of a number of advance and retreat phase tills, producing a thick marginal sequence (Figure 1.1). This model has since been modified by Evans and O'Cofaigh (2003) who propose that till thickening may occur as a result of the stacking and folding of existing sediments, therefore making the need for several readvances redundant. Both processes result in a pattern of sediment dispersal in which the till thickens towards the submarginal zone (Evans & Hiemstra, 2005).

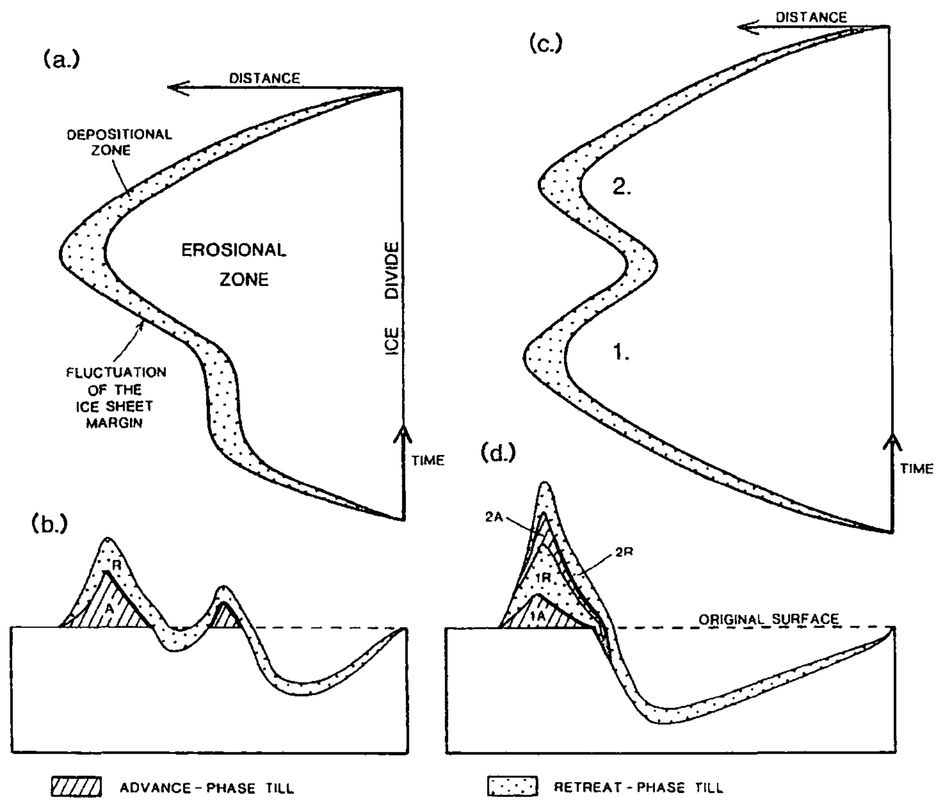


Figure 1.1. Till sequences generated by complex patterns of ice sheet fluctuations. Advance-phase tills are shaded, retreat-phase tills are dotted, and erosion surfaces are marked by a heavy line. (a-b) represents an ice sheet with a prolonged standstill period during advance. (c-d) represents stacked till sequences caused by a readvance. Boulton, 1996a, p.54.

Boulton (1996a) described the subglacial transport of sediment as the movement of discreet debris packages along different time-distance trajectories, where each trajectory is unique to a particular package. In the erosion zone, increasing sediment discharge allows these debris packages to gain new material, at a rate dictated by the rate of erosion, and therefore to continuously change composition. Consequently, a far travelled sediment package is likely to contain a diverse assemblage of minerals from various sources over which the glacier has travelled. In the depositional zone, material is deposited and the debris package composition remains the same. Figure 1.2 illustrates how the bulk composition of retreat-phase till changes over distance from the ice divide in relation to source lithologies. Retreat phase till deposited within 300km south of the ice divide is predicted to be dominated by local lithologies. Beyond 300km the model predicts that a significant proportion (up to 50%) of the till composition is made up of far-travelled material. This is due to high ice velocities and erosion rates in the outer zone during ice expansion.

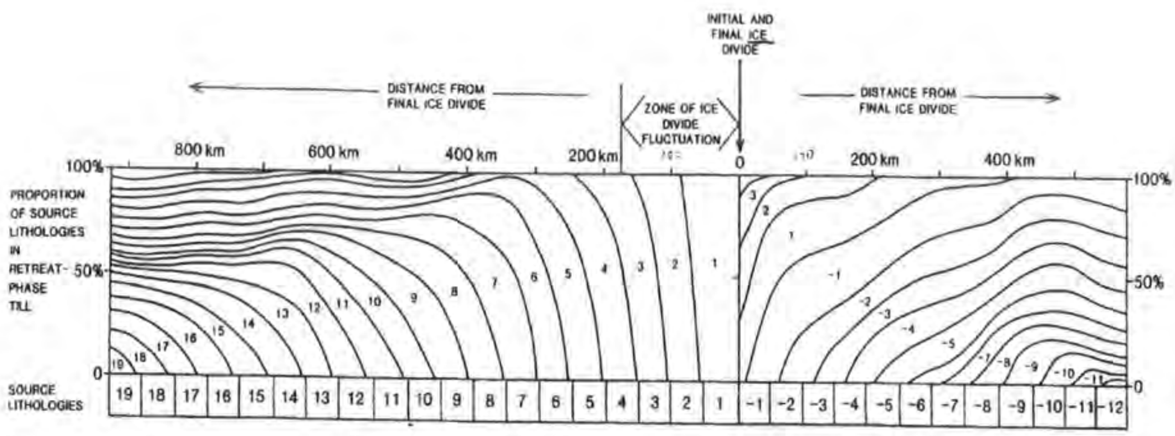


Figure 1.2. Bulk lithological composition of retreat phase tills in relation to their source lithologies. Source lithologies are shown along the bottom, where 1 to 19 are located south of the initial and final ice divide and -1 to -12 situated to the north. Proportions of individual source lithologies are shown in relation to their distance from the ice divide. NB. Material is transport across the ice divide to the north due to the southwards migration of the divide during maximum glaciation. Boulton, 1996a, p.57.

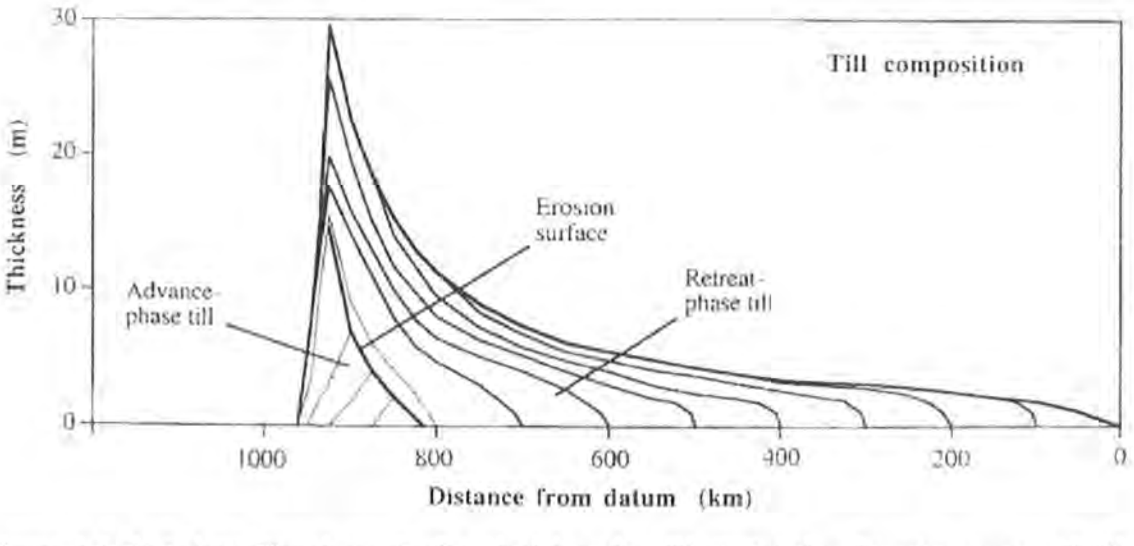


Figure 1.3. Net depositional result of a glacial cycle. Illustrates the changing source of till through time. Boulton 1996b, p.79.

In addition to examining lateral changes in till composition, Boulton was able to construct the vertical changes in till lithologies at a given point. Till deposited at one location accumulates from the deposition of a series of sediment packages travelling along different time-distance trajectories. Since all these packages are of different bulk composition, the till being deposited will progressively change composition upwards. Local material will be deposited first, and so the till sequence will show a progressive increase in far travelled material upwards (see Figure 1.3).

Geochemistry provides a novel mechanism of testing Boulton's theory through vertical changes in till petrography up sequence. The wealth of drift compositional studies by the Geological Survey of Canada (GSC) on the Laurentide Ice Sheet highlights the potential use and implications of geochemical drift prospecting (e.g. Dilabio & Coker, 1989; Kettles & Shilts, 1989; Shilts & Smith, 1989; Klassen & Thompson, 1993; Shilts, 1993). Despite most of this research being based on surficial drift prospecting investigations, a number of studies (e.g. Broster, 1986; Steele *et al.*, 1989) show the applicability of geochemistry for till differentiation and correlation in vertical profiles.

In the U.K., there has been relatively little research that has utilized geochemistry for till differentiation, correlation and provenancing (examples include Perrin *et al.*, 1979; Burek & Cubitt, 1979, 1991; Burek, 1991). Despite extensive research on geomorphological mapping, sediment stratigraphy and lithostratigraphic correlation during the last century, few reconstructions of the British Ice Sheet have been developed (e.g. Boulton *et al.* 1977, 1985), and of the few that have, they have often been compiled from a wide range of glacial research in Britain which varies greatly in terms of quality and density (Evans *et al.*, 2005). Geochemistry provides a new mechanism for the identification and correlation of till sequences. Furthermore, it cannot only be used at a local scale to test theories of till differentiation and sediment dispersal, but there is much potential for use at a regional scale for till provenancing and sediment transport history (Shilts, 1993; Perrin *et al.*, 1979).

The North Sea lobe was a Late Devensian ice lobe that advanced onshore from the North Sea Basin during the last glaciation depositing a series of tills along the east coast of England from County Durham southwards into Norfolk. Despite an abundance of sedimentological and stratigraphical data on these tills over the last 150 years, their lithostratigraphic origin remains controversial, and their correlation along the coast of eastern England is poorly understood. Madgett and Catt (1978) argue, based upon petrography, that there are only two Late Devensian tills in the region of east Yorkshire and north Lincolnshire, which have traditionally been referred to as the Skipsea and Withernsea tills. Although there appears to have been a general acceptance of this nomenclature (e.g. Lewis 1999), Evans *et al.* (1995) highlight the complexity of the Skipsea Till sequence due to the re-working and incorporation of pre-existing sediments. In addition, there is some disagreement regarding the age of the Basement Till, a till found beneath the Skipsea and Withernsea tills along the east coast of Yorkshire. Catt and Penny (1966) argue that the Basement Till underlies the Ipswichian interglacial raised beach at Sewerby, and so therefore assign the Basement Till to a glacial episode earlier than the last interglacial. Amino acid ratios, however, suggest a Late Devensian age for marine fossils within the till (Eyles *et al.*, 1994).

Differences in the mineralogy and extent of the Skipsea and Withernsea tills, have led to a number a models regarding their provenance and nature of deposition. Madgett and Catt (1978) and subsequent papers (Edwards, 1981; Catt 1987, 1991, 2007), have proposed that these tills were deposited by a 'two-tiered' ice sheet formed by the superimposition of Stainmore ice from northern England, onto the coastal ice of the North Sea lobe. In contrast, a surging model has been employed to explain the occurrence of till in this region (Boulton *et al.*, 1977; Eyles *et al.*, 1994), and Boulton (1996b) suggests that a shift in a northerly ice-divide to the south-west can explain the changes in till composition. In addition, Evans *et al.* (1995) propose that the Skipsea Till was deposited beneath active ice by a deforming till layer, where intervening beds of silts, sands and gravels represent cavity and pipe fills from a migrating drainage system.

Eastern England is an ideal location in which to test Boulton's (1996a,b) model since it is located in a former ice-marginal location, equivalent to Zones 3 and 4 of his sediment dispersal model. Vertical cliff sections can be used to test whether there is a progressive change in till provenance upwards from local to far travelled material as predicted. Whilst it is not the aim of this thesis to directly provenance the tills found in eastern England, it is possible to infer a local versus far travelled component from the suites of elements found. For example, those derived directly from local bedrock are likely contain a higher proportion of elements from chalk (see Figures 1.5 and 1.6) i.e. Ca and Sr, whilst far travelled material is likely to contain a richer assemblage of elements. Furthermore, the comparison of till composition along the east coast can be used to investigate lateral changes in till composition. In addition, as described above, several studies of till stratigraphy and sedimentology in the region indicate that the till sequences along eastern England are more complex than the work by Madgett and Catt

(1978) suggests (e.g. Madgett & Catt, 1981; Evans *et al.*, 1995). Therefore changes in geochemistry will also be used to investigate this regional complexity.

1.2 Aims

1. To investigate the model proposed by Boulton (1996a,b), where till composition progressively changes upwards in a till sequence from locally sourced sediment at the base to more distally sourced material towards the top.

2. To examine the complexity of the till sequences in eastern England, and to test the traditional stratigraphical sub-division of the tills into the Basement, Skipsea and Withernsea tills.

1.3 Research Questions

1. What are the sedimentological characteristics of each till facies, and what can be inferred about the origin of these tills?
2. What are the geochemical properties of the tills within the same exposure/location?
3. Are there geochemical differences between the same till at different sites along the east coast?
4. Can differences in the geochemical properties of the tills be used to differentiate and correlate between them, both spatially and temporally?
5. Are geochemical differences in the lateral composition of tills related to differing depositional environments or to a change in till provenance?

These aims and research questions will be answered by studying the geochemical composition of glacial sediments deposited by the Late Devensian North Sea lobe in eastern England, using a detailed sampling strategy at sites within this region. Changes in particle size distribution will be used to provide additional sedimentological data and support the geochemistry. A multivariate analytical strategy will be employed to analyse the geochemical data and to group samples by their geochemical composition. This will enable the examination of sediment dispersal patterns in this region, and will ultimately enhance understanding of the glacial dynamics of the North Sea Lobe of the Late Devensian British Ice Sheet.

1.4 Study Area

The study will focus on four sites along the east coast of England; Filey Brigg (TA 125816), Skipsea (TA 182552 - 179559), Dimlington (TA 398208 - 386223) and Morston (TF 986440); and three inland sites; South Ferriby (SE 998225), Kirmington (TA 103117) and Welton-Le-Wold (TF 284882). Their locations are shown in Figure 1.4. These sites have been chosen since they have all been previously recognised as being ice-marginal locations during the Late Devensian Glacial Maximum (Clark *et al.*, 2004). Key sites in the study will be Filey Brigg, Skipsea and Dimlington, since these locations provide the thickest sediment sections, and therefore a much more complex sedimentary succession.

The research will focus on sampling Devensian tills at these locations. At Filey Brigg investigation will centre on the two till units previously correlated to the Skipsea and Withernsea tills (Edwards, 1981). At Dimlington the Basement Till will be studied alongside the Skipsea and Withernsea tills, due to the uncertainty surrounding its age, and to provide a more complete picture of the differences in geochemical composition of tills in Holderness. At the remaining five sites research will be focused on the Skipsea Till or its equivalent (i.e. Marsh Till in Lincolnshire, Hunstanton Till in north Norfolk).

Figure 1.5 shows the bedrock geology for eastern England, whilst Figure 1.6 illustrates the bedrock geology of the whole of the British Isles for a broader perspective. All the sites in the study are located on Cretaceous Chalk bedrock, apart from at Filey Brigg, where the peninsula is formed by an outcrop of Corallian Limestone from the Jurassic period. The chalk extends substantially offshore to the west, whilst to the north bedrock consists of Lower Jurassic shales sandstones and limestones (Kent, 1980).

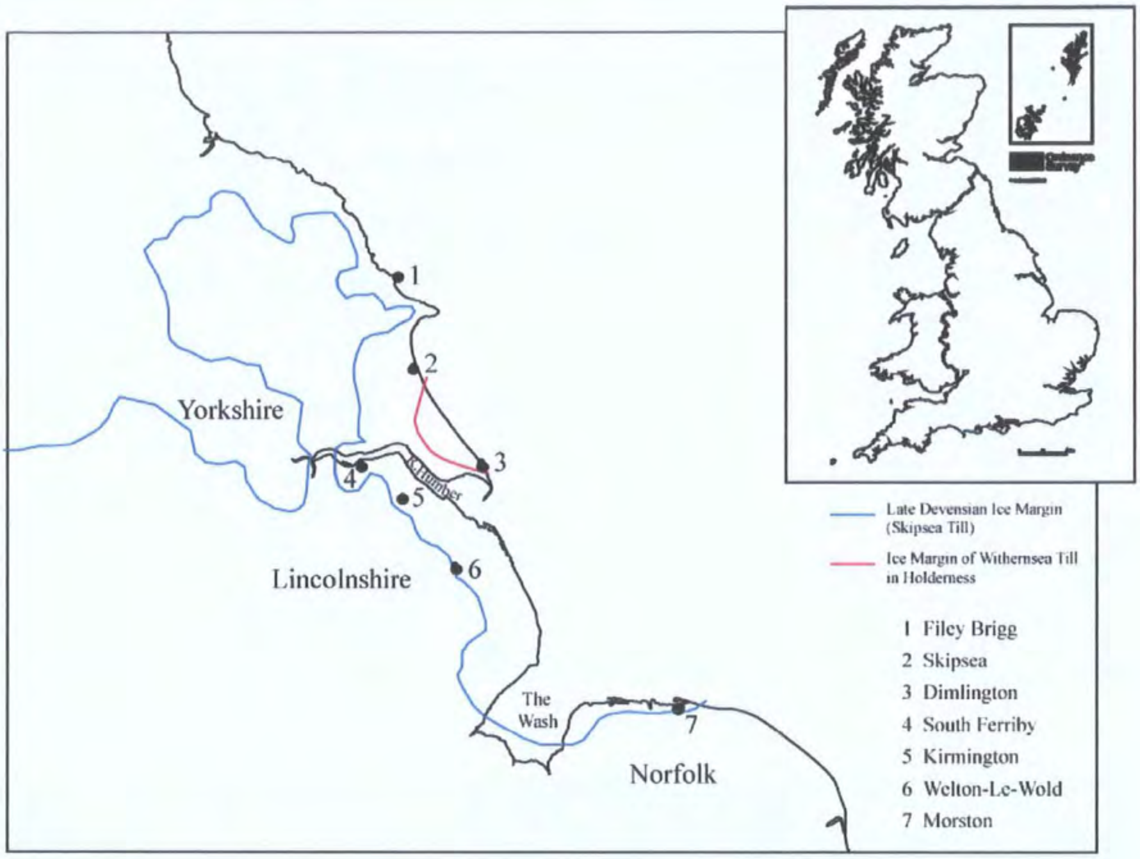


Figure 1.4. Eastern England: field site locations and other relevant sites. The Late Devensian maximum limit in this region is depicted by the edge of the Skipsea Till and outlined in blue. The Withernsea Till outcrop is highlighted in red. After Clark *et al.* (2004) and Catt (2007). Ordnance Survey © Crown copyright 2007.

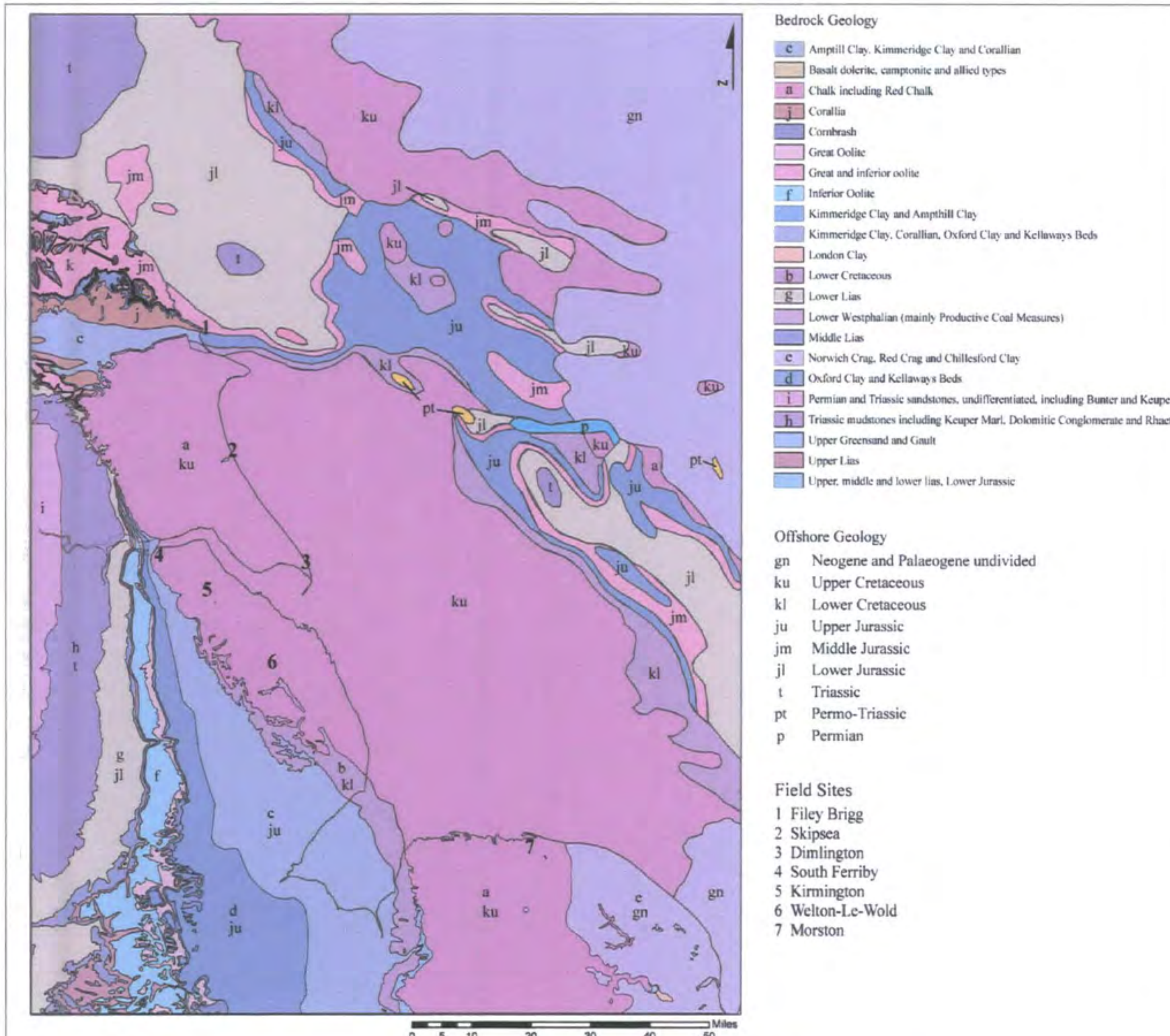


Figure 1.5. Bedrock geology of east Yorkshire, Lincolnshire and north Norfolk, including field site locations. Onshore geology: British Geological Survey Great Britain DiGMapGB © NERC 2006. Offshore Geology: BGS, 2001.

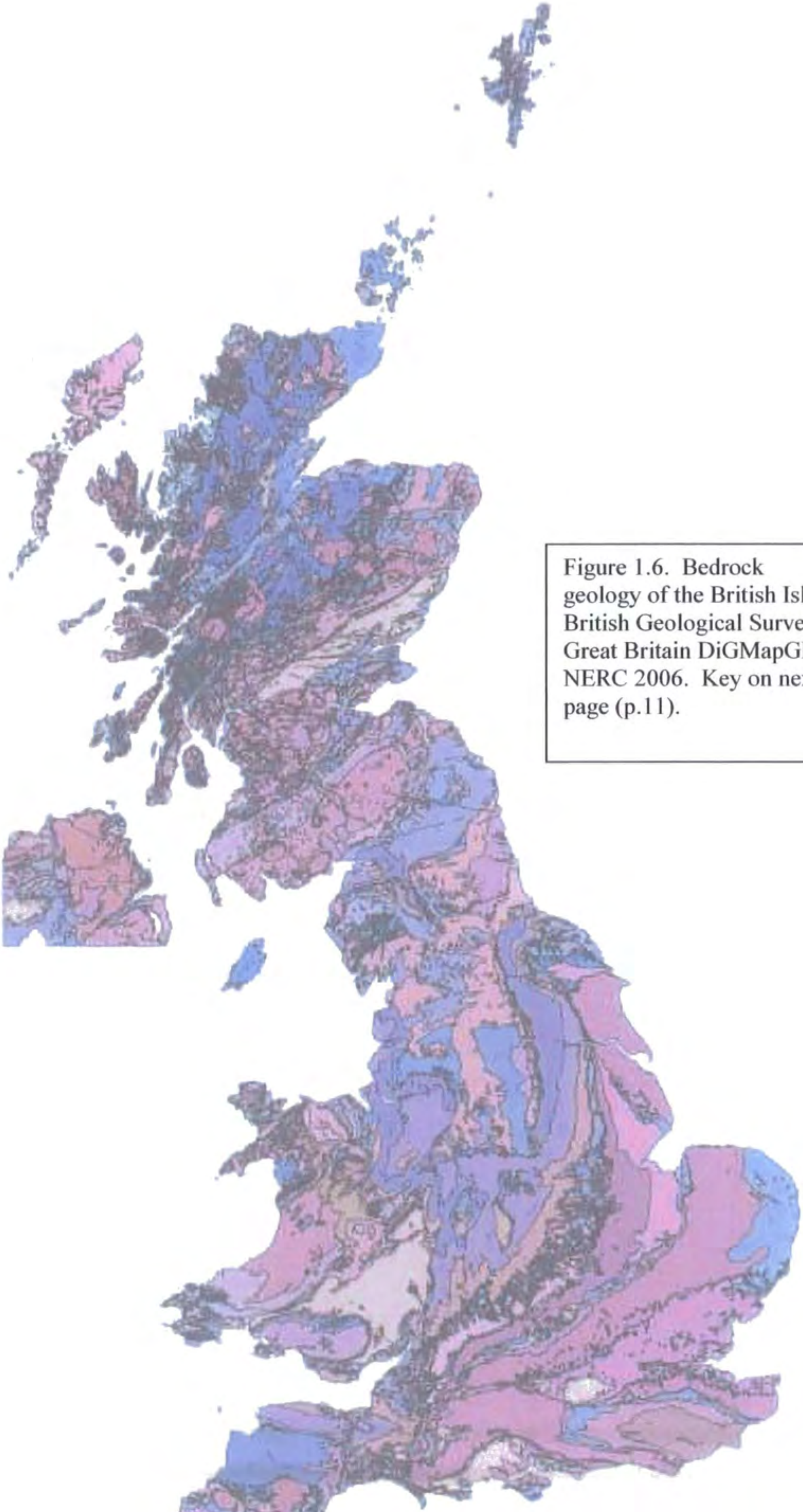


Figure 1.6. Bedrock geology of the British Isles: British Geological Survey Great Britain DiGMapGB © NERC 2006. Key on next page (p.11).

Bedrock Geology

Agglomerate in neck
Ampthill Clay, Kimmeridge Clay and Coralian
Andesitic and basaltic lavas and tuffs, undifferentiated
Andesitic lava and tuff
Andesitic lava and tuff, undifferentiated
Anorthosite
Ashgill
Ashgill and Caradoc (includes small inliers of Arenig-Llandeilo in Scotland
Barton, Bracklesham and Bagshot Beds
Basal Conglomerate (including possible Devonian)
Basalt and spilite
Basalt, dolerite, camptonite and allied types
Basalt, spilite and related tuff
Basalt, spilite and rhyolite
Basalt, spilite, hyaloclastic and related tuffs
Basaltic tuff
Black shale with chert (Upper Dalradian)
Boulder bed and conglomerate
Bovey Formation, St Agnes Sands, etc
Budleigh Salterton Pebble Beds
CAMBRIAN
Caradoc
Chalk including Red Chalk
Corallian
Coralline Crag
Cornbrash
DEVONIAN
Devonian limestone
Diorite and allied intermediate types
Durness Limestone (partly Cambrian)
Epidiorite, hornblende-schist and allied types
Epidiorite-chlorite-schist, commonly hornblendic-Green Beds
Epidiorite-chlorite-schist, commonly hornblendic-Green Beds (Upper Dalradian)
Foliated granite, syenite and allied types
Gabbro and allied types
Gneiss, mica schist
Gneissose granite, granite and pegmatite
Granite, syentie, granophyre and allied types
Granitic gneiss
Graphitic schist and slate
Gravel
Great Oolite
Great and inferior Oolite
Great and inferior Oolite and cornbrash
Greensand
Hamstead Beds and Bembridge Marls
Hastings Beds
Hornblende Schists
Inferior Oolite
Inter-lava beds
Intermediate and basic rock
Kimmeridge Clay and Ampthill Clay
Kimmeridge Clay, Corallian, Oxford Clay and Kellaways Beds
Lenham Beds
Limestone
Limestone (Upper Dalradian)
Llandeilo
Llandeilo and Llanvirn and Arenig
Llandovery
Llanvirn and Arenig
London Clay
Lough Neagh Clays
Lower CAMBRIAN
Lower Cretaceous
Lower Devonian
Lower Greensand
Lower Lias
Lower Old Red Sandstone including Downtonian
Lower Westphalian (mainly 'Productive Coal Measures')
Lower and Middle Devonian
Ludlow
Ludlow and Wenlock
Ludlow and Wenlock and Llandovery
Magnesian Limestone (Permian)
Marble
Metasediments
Mica-schist, semi-pelitic schist and mixed schists
Middle CAMBRIAN
Middle Devonian
Middle Lias
Middle Old Red Sandstone
Namurian (Millstone Grit Series)
Norwich Crag, Red Crag and Chillesford Clay
Oldhaven, Blackheath, Woolwich & Reading and Thanet beds
Open Water
Oxford Clay and Kellayways Beds
Permian and Triassic sandstones, undifferentiated, including Bunter and Keuper
Permian basal beccias, sandstones and mudstones
Permian mudstones, including Middle and Upper Marls, Eden and St Bees shales
Pipe-rock and Basal Quartzite
Porphyrite, lamporhyre and allied types
Portland Beds
Purbeck Beds
Quartz-feldspar-granulite
Quartz-mica-schist, grit, slate and pyllite (Upper Dalradian)
Quartzite
Quartzite, grit, interstratified quartzose-mica-schist
Quartzose-mica-schist
Rhyolite, trachyte and allied types
Rhyolite, trachyte, felsite, elvans and allied types
Rhyolitic and trachytic lava and tuff, undifferentiated
Rhyolitic lava
Rhyolitic tuff, including ignimbrite
Rocks of Anglesey, Lleyn Peninsular, Charnwood, Longmynd etc.
Sandstone and grit
Serpentine
Serpulite Grit and Fucoid Beds
Silurian limestone
Slate, phyllite and mica-schist
Slate, phyllite and mica-schist (Upper Dalradian)
St Erth Beds
Tournaisian and Visean (Carboniferous Limestone Series)
Triassic mudstones (including Keuper Marl, Dolomitic Conglomerate and Rhaetic)
Tuff
Tuff and agglomerate, undifferentiated, mainly basaltic
Tuff, undifferentiated
Tuff, undifferentiated, mainly andesitic
Ultrabasic rock
Undifferentiated MOINE
Undifferentiated gneiss
Undifferentiated schist and gneiss of Shetland and Central Tyrone
Upper CAMBRIAN
Upper Carboniferous
Upper Chalk
Upper Devonian and Old Red Sandstone and Middle Devonian
Upper Greensand and Gault
Upper Lias
Upper Old Red Sandstone
Upper Old Red Sandstone and Upper Devonian
Upper Westphalian, including Pennant Measures
Upper, middle and lower lias, Lower Jurassic
Weald Clay
Wenlock
Westphalian Coal Measures
Westphalian and ?Stephanian, undivided of Barren Red litholgy

Figure 1.6 *continued.* Key to British bedrock geology.

Chapter 2: Devensian Glacial History of Eastern England

2.1 Introduction

Extensive stratigraphical work has been undertaken in east Yorkshire since the late nineteenth century. Early work by Lamplugh (1879, 1882, 1891) and Bisat (1939, 1940) on the coastal stratigraphy in Holderness, east Yorkshire, was subsequently refined by Catt and Penny (1966), Madgett and Catt (1978), and more recently Lewis (1999). Radiocarbon dates from the site at Dimlington led Rose (1985) to designate this area as the UK type site for the Late Devensian Chronozone or 'Dimlington' Stadial. Elsewhere, equivalent deposits in Lincolnshire, north Norfolk and Filey Bay have been studied by Straw (1960, 1969, 1979a) and Edwards (1981), respectively. Table 2.2 summarises the nomenclature used by various authors for deposits in Yorkshire, Lincolnshire and Norfolk, and their correlation with one another. Greater detail on this earlier work is now provided. The chapter is organised firstly according to specific tills described and defined in the literature for eastern England, and subsequently by regional descriptions of previous work on the Devensian glacial history of eastern England.

2.2 The Basement Till

Boreholes at Kilnsea (Lamplugh, 1919) and Easington (Catt & Digby, 1988) show that the Basement Till (Wood & Rome, 1868) rests on the chalk bedrock surface at -30 to -35m OD (Berridge & Pattison, 1994), rendering it the oldest known till in Holderness. The till is clay-rich (see Table 2.1), dark grey in colour (Munsell Colours range between 5Y 3/1, 2.5Y 4/2 & 2.5Y 3/2), and contains a wide range of erratics from NE England, Scotland and Scandinavia (Madgett & Catt, 1978; Catt, 2007). The till is exposed in outcrops above beach level between Kilnsea Beacon and Holmpton and again in the Bridlington area (Figure 2.1), although the extent of its exposure at any one time is controlled by cliff retreat and the migration of beach ridges (Berridge & Pattison, 1994). Additionally, Basement Till has been recorded further north at Flamborough Head and in exposures at Filey Bay (Lamplugh, 1879, 1881b, 1882, 1890b, 1891, 1892; Catt & Penny, 1966; Catt & Madgett, 1981). Elsewhere along the Holderness coast, the till is believed to continue below sea-level, and boreholes suggest that it extends inland for some distance (Thomson, 2003; Evans *et al.*, 2001).

The Basement Till also contains rafts of richly fossiliferous blue-grey clay known as the Bridlington Crag (Reid, 1885) or Sub-Basement Clay of Bisat (1939), which is believed to have originated as Pleistocene marine sediment in the North Sea (Catt & Penny, 1966). Faunal lists have included shells such as *Macoma balthica* and *Arctica islandica*, gastropods, lamellibaranchs, foraminifera and marine ostracods, as well as fish teeth and vertebrate spines (Catt, 2007; Berridge & Pattison, 1994). In addition, far-travelled erratics from Scotland and Scandinavia have been found within the rafts. It has been suggested that the restricted nature of this erratic assemblage compared to the rest of the Basement Till implies that the clasts were deposited through iceberg rafting in the North Sea before being transported glacially (Catt & Penny, 1966; Catt, 2007).

Figure 2.1. Key site locations in East Yorkshire and Lincolnshire

	Basement Till	Skipsea Till	Withernsea Till
% Clay	36 - 51	22 - 38	30 - 40
% Silt	28 - 35	34 - 44	42 - 48
% Sand	21 - 39	22 - 42	14 - 25

Table 2.1. Clay, silt and sand percentages used to differentiate the Basement, Skipsea and Withernsea tills. From Catt, 2007.

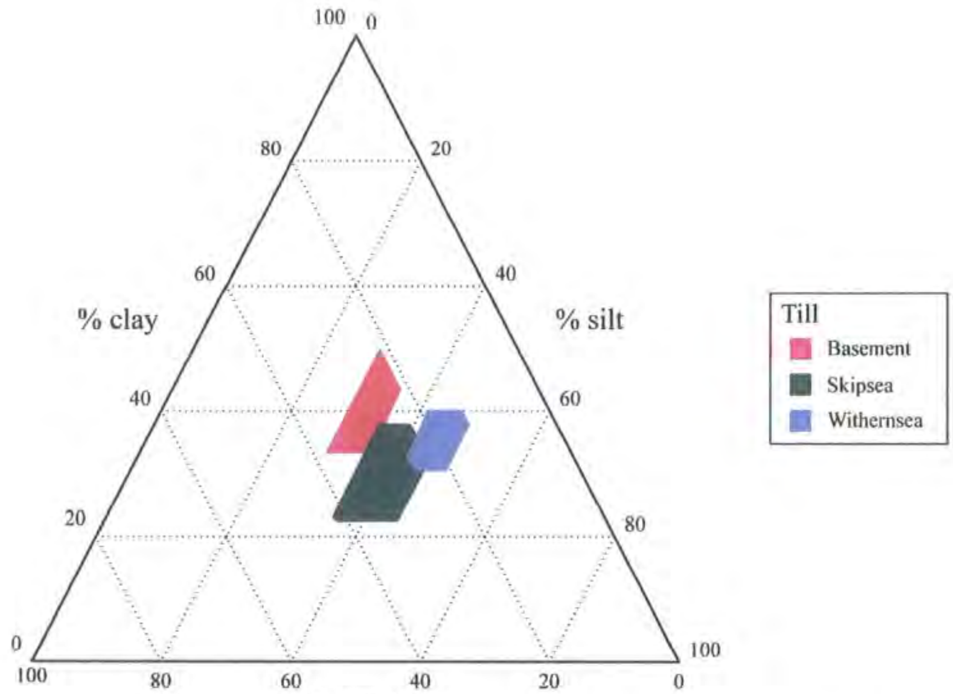


Figure 2.2. Particle size envelopes for the Basement, Skipsea and Withernsea tills. Adapted from Catt (2007).

The age of the Basement Till has been subject to prolonged debate (Bisat, 1940). Radiocarbon dates of 18,500 ± 400 ^{14}C yrs and 18,240 ± 250 ^{14}C yrs (Penny *et al.*, 1969) from moss within sand and silt filled hollows on the surface of the Basement Till imply that deposition of the till occurred earlier than the main onset of ice during the Dimlington Stadial. In addition, Catt & Penny (1966) argue that the Basement Till underlies the Ipswichian interglacial raised beach at Sewerby, and so therefore assign the Basement Till to a glacial episode earlier than MIS 5e. A pre-Devensian origin has generally been accepted and the Basement Till has been tentatively correlated with the Welton Till in Lincolnshire (Catt & Madgett in Alabaster & Straw, 1976) and the Warren House Till in County Durham (Trenchman, 1915; Catt & Penny, 1966) (Table

2.2). However, amino acid ratio analysis of marine bivalves, collected from within the Basement Till, indicate a Late Devensian age (Eyles *et al.*, 1994). This supports an earlier observation by Lamplugh (1890a, 1888, 1891) that the Basement Till in fact overlies the Sewerby Cliff Bed and thus post dates the last interglacial. Eyles *et al.* (1994) suggest that the D-alle/L-Ile ratios show the Basement Till to have been deposited not long before the radiocarbon dated silts and sands, and therefore assign its deposition to the Late Devensian. During a revision of the correlation and nomenclature of Quaternary deposits (Bowen 1999), Lewis (1999) followed this new stratigraphical order, placing the Basement Till within the Late Devensian. However, Catt (2007) argues that the dated shells in the Basement Till may have been mixed into the upper layers during deposition of the Skipsea Till.

2.3 The Skipsea Till

The Skipsea Till (Madgett & Catt, 1978) overlies the Basement Till and is separated by a discontinuous hiatus of Dimlington Silts and Sands. As discussed above, radiocarbon dates in the Dimlington Silts and Sands provide a maximum age for the deposition of the Skipsea Till and the onset of the Dimlington Stadial. It is predominantly a silty (Table 2.1), dark greyish-brown, till (Munsell Colour 10YR 3/2) and has been differentiated from the Basement Till by not only colour and texture, but also heavy-mineral and erratic content (Madgett & Catt, 1978). Chalk, flint and shale content is much greater in the Skipsea Till and increases southwards. The presence of other erratics such as rhomb porphyries, larvikite, cheviot porphyries, dolerite (Whin Sill), Juassic limestones and shales, and greywackes have led it to be traditionally assumed that the till was deposited by ice arriving from Scotland, Northumberland and the Cheviots (Catt, 2007). Stone orientations suggest deposition by ice flowing from the north-east (Penny & Catt, 1967).

Variation in the colour and erratic suites within the Skipsea Till, due to the incorporation and incomplete mixing of rafts, led Bisat to subdivide the unit. In north Holderness, he was able to make four main divisions, whilst at Dimlington he found five (Table 2.2) (Catt & Madgett, 1981). Although several possible means of correlation between the northern and southern units were suggested, Biast was unable to reach any firm conclusion, perhaps highlighting the very local, short-distance variations within the till. Evans *et al.* (1995) question the validity of these earlier complex subdivisions of the Skipsea Till, suggesting the complexity is simply a consequence of local reworking and incomplete mixing of rafts of pre-existing sediments.

In Holderness, the Skipsea Till extends substantially inland reaching a height of up to 60m at the foot of the Yorkshire Wolds escarpment, and denotes the maximum extent of Dimlington Stadial ice in this area (Evans *et al.*, 1995; Catt, 2007). Along the coast, Skipsea Till is exposed continuously, except between Holmpton and Tunstall (Figure 2.1) where it dips below beach level following the submergence of the Basement Till in this area (Catt & Madgett, 1981). Offshore the Skipsea Till is believed to be less extensive than the overlying Withernsea Till (Donovan, 1973; Cameron *et al.* 1987). However, studies have found a small outcrop, close to the coast near Easington (Donovan, 1973), and offshore in the North Sea, Carr (1999) concluded that the Boulders Bank Formation consisted predominantly of Skipsea Till.

Correlation of the Skipsea Till north and south of Holderness has been widespread. Following petrographic studies in Lincolnshire and Norfolk, the only Devensian tills in these regions, the Marsh Till (Straw, 1969) and the Hunstanton Till (Suggate & West, 1959), have both been correlated with the Skipsea (Madgett & Catt, 1978). In Filey Bay the Lower Till Series has also been correlated with the Skipsea Till based upon particle size distribution and erratic content (Edwards, 1981). Further north the lower tills of Upgang, Saltburn, and the Blackhall Till in County Durham have been correlated to the Skipsea Till (Agar, 1954; Francis, 1970; Madgett & Catt, 1981) (Table 2.2).

2.4 The Withernsea Till

The Withernsea Till (Madgett & Catt, 1978) outcrops over a small area of Holderness (see Figure 1.3) and can be seen in coastal exposures between Easington and Cowden (Figure 2.1), where it reaches a maximum thickness of 24m at Dimlington High Land (Catt, 2007). Investigations by Donovan (1973) suggest that the Withernsea Till is much more extensive offshore and constitutes a significant part of the sea floor surface. In unweathered form, the Withernsea Till is dark brown (7.5YR 3/2) and contains less sand than the Skipsea and more silt than the Basement Till. Weathering in the upper 4-5m due to pedogenesis, decalcification and the loss of some heavy-minerals has caused a reddening of the matrix to a reddish brown (5YR 3/4 – 5YR 4/4). Differences between the lower and upper units led Bisat (1939, 1940) to name these the Lower

Purple and Upper Purple tills, whilst Catt & Penny (1966) named the upper unit the Hessle Till and correlated it with a weathered unit above the Skipsea Till. However, subsequent petrographic work by Madgett & Catt (1978) showed that the Hessle Till was a weathered version of either the Skipsea or Withernsea Tills.

Colour, texture, heavy-mineral content and erratic suite are again used to differentiate the Withernsea Till from the Skipsea. Chalk and flint content increases northwards in the Withernsea Till, whilst erratics such as Shap granite from the southern Lake District indicate a more westerly origin with ice moving through the Stainmore Gap. Macrofabric analysis again indicates a NNE-SSW flow in Holderness (Penny & Catt, 1967). North of Holderness, the Withernsea Till has been correlated with the Upper Till Series in Filey Bay (Edwards, 1981), and tentatively with the upper till at Upgang and Saltburn and two intermediate tills exposed on the south bank of the Tees (Agar, 1954; Madgett & Catt, 1981) (Table 2.2).

Organic deposits found within kettle holes on the surface of the Withernsea Till near Roos provide a minimum date for deglaciation, and have been dated at 13,045 ± 270 ^{14}C yrs BP (Becket, 1981). Additional dates on similar deposits overlying the Skipsea Till at Routh (12,595 ± 80 ^{14}C yrs BP (Gearey & Lille, 2001) and at Gransmoor (12,845 ± 45 ^{14}C yrs BP (Walker *et al.*, 1993) indicate little difference between the ages of the Withernsea and Skipsea tills. Alongside radiocarbon dates from Dimlington, these deglacial dates provide a time span of about 5,500 radiocarbon years for the deposition of both tills. However, some authors (Rose, 1985; Wintle & Catt; 1985) have questioned the accuracy of these dates due to hard water errors. More recent research has suggested alternative interpretations of their age. From evidence of ice free conditions in the North Sea during the Dimlington Stadial (18,000 – 16,000 ^{14}C yrs BP; Rose, 1985) (Sejrup *et al.*, 1994), Peacock (1997) proposed that the deposition of both the Skipsea and Withernsea tills occurred after 15,000 ^{14}C yrs BP. This agrees with thermoluminescence dates from Dimlington (Wintle & Catt, 1985). Subsequently, McCabe *et al.* (1998) suggested that the deposition of both tills was even later, and associated with the Killard Point Stadial (13,785 ± 115 – 13,955 ± 105 ^{14}C yrs BP).

2.5 North East England: County Durham to North Yorkshire

Along the coast of north Cleveland, County Durham, and Tyne and Wear, three main tills are found (Catt, 1991). The oldest of these is a grey-brown till, generally known as the Lower Boulder Clay (Smith, 1981), which has been subdivided into the Wear and Blackhall tills based upon their Carboniferous and Permian erratic content (Francis, 1970). The Lower Boulder Clay (or Blackhall Till subdivision) has been correlated with the Skipsea Till in Holderness and the lowest till at Rockliffe Scar on the bank of the River Tees (Francis, 1970; Catt, 1991) (Table 2.2). A bed of sands known as the Peterlee Sands (Francis, 1970) or Ryhope Sands (Smith, 1981) separates this till from the Upper Boulder Clay, which has been subsequently named the Horden Till (Francis, 1970). This till is a reddish brown and contains cheviot erratics, demonstrating lithological similarity with the upper till in Northumberland (Catt, 1991). Despite its similarity in terms of colour to the Withernsea Till, the Horden Till lacks Lake District erratics, which are a distinctive characteristic of the Withernsea Till (Table 2.2). Catt (1991) suggests that these lithological differences between the Horden and Withernsea tills imply that ice that deposited the Horden Till did not reach as far south as Holderness. Intermediate tills at Rockcliffe Scar are more lithologically similar to the Withernsea Till, suggesting deposition of both tills by the Stainmore Ice Stream (Catt, 1991). The upper-most till is a reddish-brown silty clay which is known as the Pelaw Till (Francis, 1970) or the Pelaw / Prismatic Clay (Smith, 1981) in County Durham and the Teeside Till (Francis, 1970) in Cleveland, and has been correlated with the uppermost till at Rockliffe Scar (Francis, 1970).

In north Yorkshire, the cliffs around Filey Bay expose a thick sequence of deposits which vary significantly within the bay. At Filey Brigg, the cliffs expose 30-40m of deposits, where two till units rest upon Corallian Limestone and are separated from each other by a sequence of gravels, sands and clays (Evans *et al.*, 1995). To the south, Edwards (1987) identified a series of five 'narrow-band' till units within the Lower Till Series and overlying the Speeton Shell Bed at New Close's Cliff. During a period of about thirty years, G.W. Lamplugh recorded the stratigraphy of exposures, (Lamplugh, 1879, 1881b, 1881c, 1891). His division of the sediments is shown in Table 2.2. As in Holderness, there has been much debate about the origin of the sands and gravels, which separate the two till units and interpretations of their deposition. Fluvial (Harrison, 1895), marine (Wood, 1871) and englacial (Carruthers, 1939) environments have all been proposed, although an englacial mode of deposition has been most generally accepted.

Despite a wealth of studies by these early workers, in comparison to Holderness there has been little recent research in Filey Bay especially regarding the site's overall glacial history. Edwards (1981) redefined the two upper tills as the Lower Till Series and Upper Till Series (Table 2.2), finding a sandy lower till and clay-rich upper till. Although Edwards correlated the two tills to the Skipsea and Withernsea tills, he concluded that there was greater textural and lithological variability in the tills in Filey Bay than at Holderness. Greater variations in lithology and topography of the surrounding area, including numerous topographic barriers, were suggested to have caused this inter-till variability, and Edwards (1981) suggested that the tills were composed of local material. Edwards (1981) also proposed that these texturally and lithologically distinct rafts became incorporated into the till through a mechanism of englacial shearing.

Evidence for shearing was also found by Evans *et al.* (1995) who concluded that the tills were deposited through the accretion of a subglacial deforming till layer with a drainage network of interconnected cavities and pipes. These authors however, did not find evidence to support the division of the succession into two distinct upper and lower units. Instead, they differentiated between a massive and a laminated diamicton, where units of each were found to be repeated upwards in the sequence. Correlation of the sequence with the Skipsea Till at Holderness was only made tentatively by these authors.

The Basement Till has also been noted at Reighton and found to overlie the Speeton Shell Bed (*cf.* Austin & Evans, 1999) (Lamplugh, 1879, 1881c). Dates obtained from amino acid ratios and the pollen assemblage in this bed are conflicting, suggesting both MIS 7 and MIS 5 (West, 1969; Knudsen & Sejrup, 1988; Bowen & Sykes, 1991; Wilson, 1991). Additionally, the stratigraphic value of this bed has been questioned by Edwards (1987) who suggests that the shell bed and Basement Till are not *in situ* here.

2.6 East Yorkshire: Holderness

A significant proportion of research in eastern England has been undertaken in Holderness, particularly regarding till stratigraphy and petrography. Most regional models of ice sheet dynamics are based upon findings from the study of till sequences along the east Yorkshire coastline, but as yet, there is little agreement on the mode by which these tills were deposited (i.e. Madgett & Catt, 1978; Boulton & Dobbie, 1993; Eyles *et al.*, 1994; Evans *et al.*, 1995).

Following the glacial undermelt theory of Carruthers (1953), Madgett and Catt (1978) and subsequent workers (Catt, 1987, 1991, 2001, 2007; Edwards, 1981), have proposed that the Skipsea and Withernsea tills, and their equivalents in Filey Bay, were deposited by a single two-tiered ice sheet. Evidence for their simultaneous deposition is wide ranging and includes: 1) the lack of a weathered zone at the top of the Skipsea Till where Withernsea Till overlies it, or indigenous fossils between the two tills; 2) the lack of folding or faulted structures at the top of the Skipsea Till or in the sediments directly between them; 3) ^{14}C dates suggest little difference in the time of deposition of the two tills; 4) stratified sediments between the two tills appear to be englacially or subglacially derived which implies that ice deposited both tills simultaneously; 5) rafts of the Lower Till have been incorporated into the Upper Till at Filey Bay, and the continuation of shear planes from the Lower to Upper Till Series again suggests that the ice depositing both tills was present at the same time; 6) where kettle holes exist on the surface of the Withernsea Till, a matching depression occurs in the surface of the Skipsea Till, suggesting that the two tills acted as a single unit; 7) in order for Lake Humber to have been created, ice must have simultaneously been present in the Vale of York and in the Humber Gap. Tills in the Vale of York are believed to have a similar origin to that of the Withernsea Till, whilst ice in the Humber Gap deposited only the Skipsea Till. This implies that the two ice streams were present in Yorkshire at the same time (Catt, 2001, 2007).

Madgett and Catt (1978) envisaged that the two-tiered ice stream formed when westerly ice from Stainmore encountered east coast ice flowing from the north. The higher land of the North York Moors prevented the Stainmore glacier from flowing alongside the much larger ice sheet in the North Sea, and as a result, as it expanded it was forced to override the North Sea Ice Sheet, forming a two-tiered ice sheet. Other authors have suggested that the differences between the Skipsea and Withernsea tills can be explained by a shift in the ice divide causing a lateral shift in ice flow (Boulton *et al.*, 1977; Foster, 1987) and associated with the deposition of advance and retreat phase tills (Boulton, 1996b).

In contrast to Madgett and Catt's (1978) argument for simultaneous deposition of Late Devensian tills in Holderness, Eyles *et al.* (1994) (who interpret the Basement Till as Late Devensian in age (Section 2.1)) suggested that each till sheet in the region represents an onshore surge of the North Sea ice lobe. Boulton *et al.* (1977) in their model of the Late Devensian ice sheet in Britain recognised that steady-state assumptions could not be used to model the movement of ice down the east coast of England and therefore suggested a surging mechanism in order to explain the till limits. Additionally, Straw (1979a) suggested surging to explain the extensive southerly movement of ice with such a low profile. Eyles *et al.* (1994) believed this model for surging agreed with geomorphological and sedimentological evidence in the region. They argued that the hummocky topography overlying the arcuate belt of Withernsea Till displays a series of ridges associated with either minor readvances during retreat, or subglacial squeezing. Both mechanisms and the corresponding topography bear great resemblance to those observed at the margins of surging glaciers (e.g. Boulton & Paul, 1976; Paul, 1983; Clayton *et al.*, 1985; Drozdowski, 1987).

Discontinuous, intra- and inter-till bodies of sand, silt, clay and gravel have been observed within both the Skipsea and Withernsea tills (e.g. Wood & Rome, 1868; Catt & Madgett, 1981; Eyles *et al.* 1994; Evans *et al.* 1995). At Dimlington large bodies of laminated sand and clay can be seen to extend laterally for about 1km reaching a maximum thickness of 4m (Catt, 2007). Accounts of their exact location within the till sequence have varied through time. Cliff section logs by Bisat (Catt & Madgett, 1981) show these deposits lying within the Skipsea Till, whilst Catt and Penny (1966) found them to crop out between the Skipsea and Withernsea tills. Berridge and Pattison (1994) show the southern end of the sands and clays lying within the Skipsea Till, descending towards the Basement Till, whilst the most northern section divides the Skipsea and Withernsea tills.

Eyles *et al.* (1994) suggested that where the gravel, sand and clay units are found between the till sheets, they provide evidence for ice free periods between surges and correlated those outwash deposits at Dimlington with gravel deposits at Mill Hill near Keyingham (Figure 2.1). These gravel facies, deposited between the Skipsea and Withernsea tills, contain marine microfauna and invertebrate remains, which they argued represented the foreshore of a marine beach. Eyles *et al.* (1994) used this evidence from Mill Hill to argue that the clay and sand sequences at Dimlington were deposited in a shallow water setting of either an ice dammed lake or protected marine embayment. However, there is general agreement that during this time the southern North Sea was well above sea level (Eisma *et al.*, 1981; Lambeck, 1995; Funnel, 1995), rendering a marine beach in this location unlikely.

Furthermore, the non-fossiliferous nature of most of the inter- and intra-till deposits in the region has led many workers to conclude that they were deposited in a sub- or englacial environment (Reid, 1885). At Skipsea, Evans *et al.* (1995) noted that these features are often folded and faulted, have flat tops and convex lower contacts, and stratified diamicton is often present within them. They associated these deposits with subglacial cavity or pipe fills (Boulton & Hindmarsh, 1987; Clark & Walder, 1994), preserved after the migration of subglacial drainage channels. These 'mini-eskers' (Alley, 1991) would have opened up during the summer, but closed during the winter, causing the stratified sediments within them to became incorporated in the deforming till. Deposition of the Skipsea Till through the accretion of a deforming till layer was supported by the existence of clay-rich sediment offshore which provided a constant supply of sediment to the margin allowing till thickening caused by compressive flow (Evans *et al.* 1995; Evans & Heimstra, 2005).

Catt (2001) however, disagrees with the reliance on marine mud from the North Sea in Evans *et al.*'s deforming till model and other models for glacial surging in the region (Boulton *et al.*, 1977; Derbyshire *et al.*, 1984; Eyles *et al.*, 1994). He argues that the majority of fine material in the Skipsea Till is derived from Mesozoic and Palaeozoic mudstones, rather than Pleistocene marine sediments based upon a pollen assemblage from the Skipsea Till (*cf.* Hunt *et al.*, 1984). Catt (2001) also argues that the similarity of the tills in Holderness with till to the north of the region suggests that the Holderness tills are derived from source areas of these mudstones much further north and therefore are not locally sourced.

2.7 Lincolnshire and North Norfolk

The glacial tills in Lincolnshire play a pivotal role in the correlation of tills to the north in Yorkshire and to the south in East Anglia, and have consequently been the subject of intense study, and debate (Straw, 1958, 1969, 1979a,b, 1983, 1991; Alabaster & Straw, 1976; Perrin *et al.*, 1979; Catt, 1979, 1981). Most of this debate surrounds the pre-Devensian tills, the Welton, Calcethorpe and Wragby Tills, concerning their age, the direction of ice flow across the region during their formation, and their correlation with the Basement Till in Holderness and the pre-Devensian tills in East Anglia (Perrin *et al.*, 1979; Straw, 1983). For example, at Kirmington, Stather (1905) correlated the lower unit of till, which underlies Hoxnian interglacial deposits, to the Basement Till, therefore also assigning the Basement Till to a pre-Hoxnian stage. The till has, however, also been correlated to the Wragby Till in Lincolnshire and the Chalky Boulder Clay in Norfolk (Straw, 1969; Perrin *et al.*; 1979), which allows reconstructions in Holderness to assign the Basement Till to a younger stage (e.g. Eyles *et al.* 1994; Lewis, 1999).

The uppermost till, known as the Marsh Till (Straw, 1969), has been less controversially assigned to the Devensian glaciation (Straw, 1960, 1961) where it was first correlated to the Hessle Till (Suggate & West, 1959; Catt & Penny, 1966). However, whilst Catt and Penny (1966) and Madgett and Catt (1978) assigned all Devensian deposits in Holderness and their equivalents in Lincolnshire and Norfolk to the Late Devensian (Dimlington Stadial), Straw (1979b, 1980) argued that there was evidence for two advances during the Devensian, and that the earlier of the two advances may have occurred during the Early Devensian. This argument was based upon the evidence for two lake levels in Lake Humber. Straw (1991) suggested that the higher lake level must have been contemporaneous with a proglacial lake in the Fen basin, and therefore the ice which blocked the Humber at this stage, must have extended as far as north Norfolk. This ice deposited the more extensive Lower Marsh Till in South Ferriby, Kirmington, Welton-Le-Wold and Morston, which Straw (1969) correlated to the Drab Till (now Skipsea Till, Madgett & Catt, 1978) (Table 2.2). In a second advance, a less extensive ice sheet blocked the Humber again, creating a much smaller lake, and till was only deposited in Lincolnshire to the west of the Hogsthorpe- Killingholme line (see Figure 2.1). Straw (1969) correlated this advance with the advance in Holderness, which deposited the Purple Till (=Withernsea Till, Madgett & Catt, 1978), thus correlating the

Upper Marsh Till with the Withernsea Till (Table 2.2). The proposal for two Devensian advances in Lincolnshire is supported by Bowen *et al.* (2002) who suggested a much more extensive Early Devensian glaciation in Britain. Madgett (1975), however, found no difference in the mineralogy of the Upper and Lower Marsh Tills and accordingly correlated both of them with the Skipsea Till in Holderness.

The cliffs at Red Cliff and South Ferriby (north and south of the River Humber) provide the best record of the glacial history in the Humber Gap. The sites mark what is believed to be the furthest extent of Devensian ice in the Humber Gap where ice moved into and blocked the Humber Gap from the east (Evans *et al.*, 2001; Frederick *et al.*, 2001; Clark *et al.*, 2004). Although Straw (1969, 1991) argues that Lake Humber formed on two separate occasions during the Devensian, Gaunt (1976, 1981) suggests that following ice retreat, the initial 33m OD lake level was reduced to a much shallower lake, impounded by a moraine situated between North Ferriby and South Ferriby.

The cliffs on the south bank are located about 1km northeast of the village of South Ferriby and the glacial succession rests upon brecciated chalk bedrock (Frederick *et al.*, 2001). Examination of previous work at this location by Stather (1896) and Penny *et al.* (1972) indicates that despite coastal erosion the sequence of deposits here has remained fairly similar in the last 100 years. Stather (1896) concluded that there were two tills in this succession separated by a laminated unit, but subsequent authors have argued that differences in the two units are merely a product of Holocene weathering (Madgett, 1975; Frederick *et al.*, 2001). Straw (1969) included the till at South Ferriby in the Lower Marsh Till division and therefore correlated it to the Skipsea Till in Holderness, a correlation which has been accepted by later authors (Madgett & Catt, 1978; Frederick *et al.*, 2001).

The origin of the laminated sediments between the two till units and its relationship with proglacial Lake Humber is still unclear. Ripples are well preserved within the sand laminations and the unit thins and eventually disappears to the west. Stather (1896) suggested that the sediments were associated with a linear pool which formed between the ice margin and the higher topography to the west. In accordance with this, Frederick *et al.* (2001) suggested deposition by water flowing into a still body of water, but were reluctant to assign it to a proglacial or englacial origin.

The Hunstanton Till unit (Suggate & West, 1959) in North Norfolk records the southern-most limit of the Devensian ice sheet on the east coast of England (Suggate & West, 1959; Straw, 1960; Gale *et al.*, 1988). Several authors have envisaged that the ice which deposited this till would have had been constrained from further forward movement by the higher ground to the south (Solomon, 1932; Gale *et al.*, 1988). A small site overlying marshes to the west of the village of Morston is of great significance to the Quaternary record since the raised beach found there not only underlies glacial till, but is underlain by a second unit of till which Gale *et al.* (1988) correlate with the Marly Drift in East Anglia.

Original work at Morston (Solomon, 1931, 1932) correlated the upper diamicton with the Hessle Till of Yorkshire and Lincolnshire. Since subsequent work has revealed that the Hessle Till is a weathered version of the Skipsea and Withernsea tills (*cf.* Madgett & Catt, 1978), the Hunstanton Till is now correlated to the Skipsea Till in Holderness (Madgett, 1975). Soloman (1932) found that this diamicton contained very little chalk, and included erratics of dolerite, dark-blue greywacke and porphrites from the Cheviots. Additional erratics of flint, sandstone, quartzite, granite and other igneous clasts have since been found by more recent studies (Gale *et al.*, 1986, 1988). Gale *et al.*, (1988) suggested that the absence of chalk and marine fossils within the till indicated that the unit had been subject to intense weathering during the Holocene. Particle size analysis found a biomodal distribution suggesting that the diamicton may have been reworked and therefore may not be *in situ* (Gale *et al.*, 1986). However, further work by these authors (Gale *et al.*, 1988) found that only the upper units had been reworked from the underlying till.

2.8 Summary

The three main tills found within Eastern England and central to this study are the Basement, Skipsea and Withernsea tills. The Basement Till is the oldest known till in Holderness, is dark grey (5Y 3/1, 2.5Y 4/2, 2.5Y 3/2) and contains a wide range of erratics form NE England, Scotland and Scandinavia. There is a prolonged debate surrounding the age of the Basement Till. Whilst a pre-Devensian age has generally been accepted (Penny *et al.* 1969), amino acid ratio analysis places the Basement within the Devensian period (Eyles *et al.* 1994; Bowen, 1999). Most correlations of the Basement Till with other tills north and south correlate it to other pre-Devensian tills e.g. the Welton Till in Lincolnshire (Catt & Madgett in Alabaster & Straw, 1976) and the Warren House Till in County Durham (Trenchman, 1915; Catt & Penny, 1966).

The Skipsea Till (Madgett & Catt, 1978) overlies the Basement Till and is separated by a discontinuous hiatus of Dimlington Silts and Sands. Radiocarbon dates on these sediments provide a maximum age (c.18,500 ^{14}C yrs) for the deposition of the Skipsea Till and the onset of the Dimlington Stadial. The till is dark greyish-brown (10YR 3/2) and contains a suite of erratics that have led it to be traditionally believed that the till was deposited by ice originating in Scotland, Northumberland and the Cheviots. The Skipsea Till, previously known as the Drab Till (Catt & Penny, 1966) has been correlated with the Lower Marsh Till in Lincolnshire (Straw, 1969), the Lower Till Series in Filey Bay (Edwards, 1981), the lower tills of Upgang and Saltburn and the Blackhall Till in County Durham (Agar, 1954; Francis, 1970) (see Table 2.2).

The Withernsea Till is confined to a much smaller area of Holderness than the Skipsea Till. In unweathered form the till is dark brown (7.5YR 3/2), but weathering in the upper 4-5m has caused a reddening of the matrix (5YR 3/4 – 5YR 4/4). The weathered section has previously been assigned to a separate unit known as the Upper Purple Till (Bisat, 1939, 1940) or Hessle Till (Catt & Penny, 1966), but Madgett and Catt (1978) have subsequently shown that the Hessle Till is a weathered version of the Skipsea or Withernsea tills. North of Holderness, the Withernsea Till has been correlated with the Upper Till Series in Filey Bay (Edwards, 1981) and tentatively with the upper till at Upgang and Saltburn (Agar, 1954). To the South, Straw (1969) correlated the Withernsea Till with the Upper Marsh Till of Lincolnshire, however, Madgett (1975) found no difference in the mineralogy of the two Marsh tills and correlated both of them with the Skipsea Till (Table 2.2).

Most regional models of Late Devensian ice sheet dynamics in the east of England are based upon research in east Yorkshire, but as yet there is little agreement on the mode of till deposition. Madgett and Catt (1978) proposed that the Skipsea and Withernsea tills were deposited by a single two-tiered ice sheet, due to evidence for their simultaneous deposition. It was envisaged that this occurred when ice flowing from the west through the Stainmore gap met and overrode ice flowing from the north down the east coast. However, other authors have suggested that differences in the provenance of the Skipsea and Withernsea tills can be explained by a shift in the ice divide causing a lateral shift in ice flow (Boulton *et al.*, 1977; Foster, 1987) and associated it with the deposition of advance and retreat phase tills (Boulton, 1996b). Alternatively, Eyles *et al.* (1994) suggested that each till sheet represents an onshore surge of the North Sea ice lobe, after finding geomorphological and sedimentological evidence for surging. Surging has also been suggested by Boulton *et al.* (1977) in their model of the Late Devensian British Ice Sheet.

Further south, Straw (1979b, 1980) argued that the tills in Lincolnshire are the product of two advances during the Devensian. The first advance, argued to have occurred during the Early Devensian, deposited the Lower Marsh Till, which is correlated to the Skipsea Till, whilst the second advance deposited the Upper Marsh and Withernsea tills. This proposal is supported by Bowen *et al.* (2002) who suggested a much more extensive Early Devensian glaciation in Britain.

The origin of discontinuous, intra- and inter-till bodies of stratified sediments has also been contested, where accounts of their exact location between and within the Skipsea and Withernsea tills have changed over time (*cf.* Bisat in Catt & Madgett, 1981; Catt & Penny, 1966; Berridge & Pattison, 1994). Eyles *et al.* (1994) suggested that where these sediments lie between till sheets, they provide evidence for ice-free periods between surges and correlated those outwash deposits at Dimlington with gravel deposits at Mill Hill near Keyingham. However, the non-fossiliferous nature of most of the sediments has led many workers to conclude that they were deposited en- or subglacially. Accordingly, Evans *et al.* (1995) associated the deposits with subglacial cavity of pipe fills (Boulton & Hindmarsh, 1987; Clark & Walder, 1994), where they were deposited through the accretion of a deforming till layer.

Wood & Rome (1868)	Bisat (1939, 1940)	Catt & Penny (1966)	Madgett & Catt (1978)	Lewis (1999)	Francis (1970)	Lamplugh (1879)	Edwards (1981)	Straw (1969)
Holderness					County Durham	Filey Bay	Northeast Yorkshire	Lincolnshire
					Pelaw Till			
					Horden Till			
Hessle (boulder) Clay	Upper Purple Clays (2 beds)	Hessle Till	Withernsea Till			Hessle Till	Upper Till Series	Upper Marsh Till
Hessle sand (or gravel)	Gravels			Flamborough Member		Patches of gravel		
				Hornsea Member				
Purple Clay	Lower Purple Clays (3 beds)	Purple Till		Withernsea Member		Brown Till		
	Silt, Sand & Gravel			Mill Hill Member	Peterlee Sands	Gravel	Gravel	
Purple Clay & Bridlington Crag	Upper Drab Clay Middle Drab Clay Chalk rafts Lower Drab Clay Sub Drab Clay Basement Drab Clay	Drab Till	Skipsea Till	Skipsea Member	Blackhall Till	Greenish-Purple Till	Lower Till Series	Lower Marsh Till
Sands & Gravel (+ clay)		Dimlington Interstadial Beds	Dimlington Silts	Dimlington Bed		Gravels, sands & silts (Laminated beds)		
Bridlington Crag in Basement Till Basement clays of Holderness	Basement Clay Sub Basement Clay	Basement Series	Basement Till	Bridlington Member		Basement Till Chalk rubble	Chalk rubble Basement Till Chalk rubble Speeton Shell Bed	

Table 2.2. Summary of nomenclature used to describe Devensian glacial deposits in eastern England. Adapted from Straw, 1979; Madgett & Catt, 1981; Evans *et al.* 2001.

Chapter 3: Methods

3.1 Introduction

This chapter reviews the methods used during sample collection and analysis for the geochemistry and particle size analysis. A background into previous geochemical research in the literature is provided, which includes justification for the methods used in this thesis. Evaluation of the errors associated with the sampling and laboratory methods used is presented towards the end of this chapter.

3.2 Field Methods

3.2.1 Section logging

Exposures of diamictons, sands, clays and gravels were logged in detail using sketches, vertical lithofacies logs and photographs. The sections were examined in detail with regard to structural characteristics, sediment architecture, sorting and texture, bed contacts, unit geometry, and colour using a Munsell Colour Chart, to provide a sedimentological context for the geochemical data. This data was logged using lithofacies codes adapted from Benn and Evans (1998), Eyles *et al.* (1983) and Krüger and Kjaer (2000), which are listed on p52. The results were used to identify facies associations at each site for more detailed analysis and interpretation.

3.2.2 Sampling Strategy

In locations such as Skipsea and Dimlington, the extensive cliff exposures, displayed lateral and vertical changes in sedimentology and stratigraphy. For example, intervening laminated sand or clay units were found at some sections, but disappeared laterally along the cliffs. The relative thickness of these units also changed laterally. Therefore, at each site, samples were taken from more than one section in order to obtain a broader picture of the sediment assemblages found. This also facilitated inter-site comparison and inter-section comparison at the same site. The location of each section was chosen carefully in order obtain a collection of samples representative of the location as a whole. However, in practice, the choice was often determined by the availability of suitable sections. Slumping was widespread along the coastal cliff sections of east Yorkshire, and many of the sections that were not slumped were too vertical to sample safely.

Where possible, sampling was carried out along a continuous vertical transect, but due to the availability of suitable sections at some locations (Skipsea, Dimlington and Filey) this was often impossible. Therefore some sections are based upon two or more sub-sections that are in close proximity and can be correlated up the cliff. Sampling was systematic where possible and taken at 0.5m intervals. However, at some sections more detailed sampling was carried out in order to include all the changes in sediment type or composition. The height of each sample was recorded, and its location logged on a field sketch or lithofacies log.

3.3 Geochemical Analysis

3.3.1 Background

Geochemical exploration has been fundamental to Quaternary glacial geological research in Canada since the 1960s. Originating in Fennoscandinavia, the technique of glacial indicator tracing was developed through a need for better methods of mineral exploration in glaciated terrain. Rapid advances in Canada since this time have revolutionised the mineral industry through focussing on the provenance of glacial sediments, which can indicate the source of a particular ore (Shilts, 1993). The increased use of drift geochemistry in particular, has led to the detection of a large number of dispersal trains, which have not only led to the discovery of several new ore deposits, but have also provided new data on the flow directions of past ice sheets (Saarnisto, 1990). For example, based upon increasing support from drift compositional studies around Hudson Bay the concept of a single-domed Laurentide Ice Sheet was replaced by that of a multi-dome model (Shilts *et al.*, 1979; Dyke *et al.*, 1982; Shilts, 1993).

The distribution of particular elements within glacial deposits is influenced by the presence of certain minerals. Minerals are released from rocks through weathering processes and mechanically through glacial erosion. Glaciers initially erode fragments of bedrock which are subsequently ground into smaller grains by abrasion and thus the geochemistry of glacial sediments is directly associated with the geology of the bedrock over which a glacier flows. Therefore, in general, it is only the finer fractions of the matrix that will contain a rich assemblage of elements and glacial sediments that have been deposited close to their source area are likely to be geochemically immature (Burek & Cubitt, 1991). Glaciers disperse material in a way that the peak of a particular mineral concentration occurs at or soon after its source, and then decreases in the form of an exponential curve. Reconnaissance scale sampling in Canada aims to find the dispersal 'tail' of this pattern (Shilts, 1976). In areas of cross-cutting ice flow, the signal may be much more complicated, where this pattern is affected by the underlying older flow units (Veillette, 1986; Bouchard & Marcotte, 1986; Klassen & Thompson, 1989). Prior glacial knowledge of the area is therefore vital in recognising the effects of contrasting stratigraphic units (Saarnisto, 1990; Shilts & Kettles, 1990).

Post-depositional weathering has a significant effect on the composition of tills and it is also important to understand the vertical changes that this may cause (Shilts & Kettles, 1990). This importance is highlighted in Holderness, where Madgett and Catt (1978) showed that the differences between un-weathered and weathered till from the same unit had led to its division into two stratigraphic units believed to have different provenances. Burek and Cubitt (1991) stress the importance of rock type and climate in influencing weathering. Differences in the degree of processes such as leaching and oxidation in tills are likely to be a function of their geochemical composition. For example, calcium compounds such as CaO and $CaCO_3$ are soluble in acidic conditions and so are easily leached in a wet temperate climate, whilst silica remains stable in most conditions (Burek & Cubitt, 1991). Several authors therefore suggest that direct sampling of weathered drift for prospecting purposes is likely to yield uninterpretable results due to the over-representation of stable minerals (Shilts & Smith, 1989; Shilts & Kettles, 1990). However, in this research samples were collected from weathered till in order to assess changes in matrix geochemistry between weathered and unweathered samples.

It has also been proposed that the range of grain sizes used for geochemical investigations can also affect the suites of elements found. Whilst Burek and Cubitt (1991) suggest that it is only the finer grain-size fractions that will yield a rich assemblage of elements, studies have shown that these finer fractions may be biased towards the dominance of less-resistant minerals (Dreimanis & Vagners, 1969, 1971a,b; Broster, 1986). Other studies have also shown differences in weathering effects depending on the grain size fraction (Shilts & Kettles, 1990). In this research geochemical samples were taken from a grain size range of less than 2mm, in order to provide a wider range of grain sizes, therefore reducing bias towards less-resistant minerals and not isolating particular weathering effects.

In Canada, although most studies have used geochemical analysis to map concentration patterns of elements over a whole region, some used geochemistry to differentiate stratigraphic units within a vertical section (May & Dreimanis, 1976; Broster, 1986; Steele *et al.*, 1989). Although several studies have suggested that till composition transitionally changes upwards from locally to more distally derived sources (Moran, 1971; Shilts, 1978), most geochemical studies of vertical sequences have used the technique to focus on differentiating between stratigraphic units (e.g. May & Dreimanis, 1976; Steele *et al.*, 1989). The current research presented in this thesis differs from these studies since it uses a more objective approach to geochemical differentiation. Geochemical groups will be decided based upon the results of cluster analysis (*cf.* Section 3.3.3), rather than comparing the geochemical differences between pre-defined till units. This it is hoped will provide a more objective approach.

In the U.K., the use of geochemistry has been limited and has not occurred on such a large scale. A number of studies have investigated changes in heavy mineral and calcium carbonate composition (e.g. Madgett & Catt, 1978; Perrin *et al.*, 1979; Lee *et al.*, 2004), but very few have utilised trace elements. The most extensive use of geochemistry has been undertaken by Burek (1985a,b; Burek & Cubitt, 1979, 1991) in relation to the mid-Pleistocene tills in Derbyshire. Multivariate statistical analysis showed that the British tills in Burek and Cubitts's (1991) study could be divided into three groups. A major division between most British tills was caused by the amount of CaO and it associated trace element Sr within each till. Tills from the western side of the Pennines grouped together with low CaO percentages (less than 10%), whilst calcium-rich tills in eastern England were also grouped together, demonstrating the importance of local bedrock geology in till geochemistry. Tills from Derbyshire formed the third group being too calcareous to be assigned to the western till group, but too different in general element suite to be similar to the eastern tills, again inferring a local origin for tills deposited in this area and supporting an argument that the influence of the North Sea and Irish Sea ice was limited in the production of tills in North Derbyshire.

More detailed principle component and cluster analysis was able to subdivide the Derbyshire tills further. Principal components analysis found that the main component represented the influence of shale and dolerite on the tills, the second component represented the clays versus non-clays and the third component represented a carbonate versus non-carbonate association. Results of the cluster analysis divided the tills into seven cluster groups, which predominantly corresponded to their location, again demonstrating the importance of local geology in the composition of tills. This research therefore highlights the applicability of multivariate statistical analysis for examining this kind of data and a similar approach will be used to analyse the data set in the current research (*cf.* Section 3.3.3).

3.3.2 Laboratory Methods

Sample Preparation

All samples taken in the field were analysed for geochemistry. Approximately 3g of each bulk sample matrix (< 2mm) was taken and placed in a -80°C freezer overnight. After a subsequent 24 hours of freeze drying, the samples were crushed in a planetary ball mill (*Fritsch* Pulverisette 6) and stored at 20°C in a desiccator. An extraction program based on EPA method 3052 was used. 250mg of each sample was weighed into an HF resistant microwave extraction vessel. The internal wall of each vessel was rinsed with 5ml of deionised water to remove any sample from the sides, 2ml of concentrated hydrogen peroxide (100 volumes = >30% w/v) was added to dissolve any organic material, and the samples left to react overnight. 9ml of HNO_3, 3ml of HCL, and 2ml HF were then added (EPA method 3052) to dissolve the sample. The vessels were then capped and placed in a MARS pressurised microwave extraction system (reaching 180 ± 5°C in less than 5 minutes and remaining at this temperature for 9.5 minutes). The samples were left to cool to 40°C before being removed, and were subsequently filtered into Class A 100ml plastic volumetric flasks through pre-washed Whatman 542 filter paper, and made up to the mark with deionised water. An appropriate aliquot of this solution was taken and made up to 90ml with 2% v/v nitric acid in a 100ml plastic volumetric flask. 1ml of the appropriate internal standard solution was then added to the flask and the solution made up to the mark with more 2% v/v nitric acid.

ICP-MS Total Metals Extraction (HF-HCL-HNO_3)

Initial investigation of suitable elements for the study was undertaken using the ICP-MS Total Quant method, which uses a semi-quantitative technique to estimate element abundances. This method was carried out on twelve selected samples from Skipsea. Elements were selected which had substantial abundances in all or most samples, or elements that showed significant changes between samples. The suite of elements requested was: high abundance – Al, Ca, Fe, K, Mg, Na, P, Si, Ti; low abundance – Ag, As, B, Ba, Be, Bi, Cd, Ce, Co, Cr, Cu, Ga, Li, Mn, Mo, Nb, Nd, Ni, Pb, Rb, Sb, Se, Sn, Sr, Th, Tl, U, V, Y, Zn, Zr (see Appendix i for full element names).

The ICP-MS settings and internal standards for the Total Metals Extraction were based on EPA method 200.8 r5.4, and the internal standards included Rh_{103}, Tb_{159}, Re_{185} and In_{115}. The internal standards gave a final concentration of 50ppb in both standards and samples, and the suite was split into two runs, for high abundance and low abundance elements.

3.3.3 Statistical Methods: Cluster Analysis

Hierarchical cluster analysis was used in this research as a means of assembling the samples into groups containing similar suites of elements. The technique was used as an exploratory data analysis tool (StatSoft, 2007), rather than a tool for data reduction (Rogerson, 2001). For this purpose, a number of clustering methods were used to assess the geochemical similarity of samples independently from the method of clustering used. Due to the quantity of data, cluster analysis was initially performed for each location separately and groups of geochemically similar samples were established at each location. The dissimilarity level at which cluster groups were selected was guided by the level of similarity shown by repeat samples (*cf.* Section 3.5.1). The 'cut-off' level was also chosen based on a dissimilarity that would produce meaningful groupings. Once the cluster groups had been decided, the abundances of each element within a group were averaged, and cluster analysis was performed on these group averages to determine which groups and locations were similar. All the methods were performed using the statistical program *Stata*.

Cluster analysis was first performed using the complete linkage method. Initially, individual samples represent their own cluster, and the distance between the samples is determined by the chosen distance, in this case the Euclidean distance. The Euclidean distance measures the geometric distance in multidimensional space (StatSoft, 2007), where the larger the distance the higher the dissimilarity between groups (Davis, 2002). Once clusters of samples have been formed, the complete linkage method determines the distance between cluster groups using the maximum distance of any two samples in the two clusters (Rogerson, 2001; StatSoft, 2007). The method was chosen since it produces good cluster groupings when the samples fall naturally into distinct groups (StatSoft, 2007).

However, it soon became apparent after producing some preliminary clusters that although most samples formed groups, some formed "chain" type clusters. The use of the complete linkage method is less appropriate for chain-type data (StatSoft, 2007), and therefore Ward's method was used as an alternative method of cluster analysis. This method merges clusters that result in the smallest increase in the sum of the squares of the new cluster, and as a result minimises the within-group variability (Rogerson, 2001). For this method, the squared Euclidean distance was used to measure the dissimilarity. By squaring the standard Euclidean distance greater weight is placed on samples that are further apart, creating more defined clusters (StatSoft, 2007).

Euclidean distances can be significantly affected by the differences in scale, and the distance is most affected by variables with large magnitudes (Davis, 2002; StatSoft, 2007). To avoid this bias, the data was transformed into z-scores in order to standardise the data, where a z-score is defined as:

$$z = \frac{x - \bar{x}}{s}$$

where: $x =$ sample

$\bar{x} =$ sample mean

$s = \sqrt{\text{sample variance}}$ = sample standard deviation

A z-score can be interpreted as "the number of standard deviations an observation is away from the mean" (Rogerson, 2001, p.7). Initially, z-scores were calculated for each element using all of the data. This meant that the mean used in the calculation was a mean for all the abundances for that element. Since over one hundred samples were taken at Dimlington compared to only two at Morston, it became apparent that locations where a large number of samples had been taken were likely to bias the z-scores, and therefore influence the cluster analysis. Since variation within locations was investigated first, before comparison with other locations, z-scores were also calculated for individual locations, to remove any bias. The results shown in Section 4.3, do show significant changes in the cluster groups at each location using combined z-scores and individual z-scores, although the most significant differences occur at the larger sites, perhaps due to the larger number of samples and clustering possibilities. However, although using individual z-scores removes the influence of other locations, it hinders comparison between locations, since the Euclidean distances are no longer comparable. The advantage of using combined z-scores is that the same dissimilarity level for clusters at each location can be used to produce overall geochemical groups in the study. Consequently the complete linkage and Ward's methods for cluster analysis were both carried out using combined and individual z-scores, creating four different cluster dendrograms and geochemical groups.

3.4 Particle Size Analysis (< 2mm)

Samples used for less than 2mm matrix particle size analysis were selected at roughly 1m intervals from the vertical log. This interval was again increased or decreased depending upon the complexity of the section. For samples at most locations, an appropriate mass of < 2mm matrix was removed at random from the selected bulk samples (for clays ~ 0.2g, diamictons ~ 0.6g, sands > 1g) and placed in a 50ml test tube. However, due to initial experimentation with the sampling and sieving strategies for particle size, the method used for Skipsea samples varies from the rest of the study. Bulk samples were wet-sieved by hand through a 2mm sieve, and sediment below 2mm was retained with the intention that once dry a small sample of this matrix would be selected using a riffle box for particle size analysis in the coulter granulometer. Problems with sample aggregation while drying meant that this method was unfeasible and very time-consuming. In order to shorten the length of time required, samples were taken from a thoroughly mixed wet sample of the < 2mm matrix. Errors associated with this method are discussed in Section 3.5.2.

An excess of 20ml of 20% hydrogen peroxide was added to each sample, and then placed in a boiling water bath until all the organic material had been dissolved (at least overnight). The samples were then topped up to equal levels with distilled water and centrifuged at 4000rpm for 4 minutes. The supernatant water was decanted off and the process repeated to ensure all remaining hydrogen peroxide was removed as this can affect the coulter results. 20ml of distilled water was then added to each tube along with 2ml of sodium hexametaphosphate solution as a deflocculant.

Samples were analysed for particle size using the *Beckman Coulter LS 13 320* Laser Diffraction Particle Size Analyser. Two runs were carried out for each sample and an average taken provided that the results graphs were similar. Personal judgment was used to determine this. If the results were too dissimilar two more runs were undertaken and compared. If, after six runs, none of the two runs were similar, an average of all six was taken.

3.5 Errors

3.5.1 Geochemical Analysis

Sampling Error

In order to assess the error in sub-sampling a particular bulk sample, five sub-samples were taken from sample D5.12 using the method described in Section 3.3.2. Standard deviations for the abundances of each element are shown in Table 3.1. Variation between the repeated samples appears relatively high, which means that there may be some variation within the matrix geochemistry within a relatively small volume of diamicton.

Cluster analysis using both the complete linkage and Ward's methods (*cf.* Section 3.3.3.) was performed on the repeated samples. First the repeated samples were added to the data from all the sites instead of the average for D5.12 used in the main analysis, and z-scores were calculated. Figure 3.1 shows the cluster dendrogram for the repeated samples. Although the z-scores used in this cluster analysis are not identical to those used for the combined z-score cluster analysis, they are similar enough that they can be used to identify a level of similarity from which cluster groups in the main analysis can be classified. All five repeated samples cluster together at a Euclidean distance of just above 5, and a squared Euclidean distance of 31. Therefore samples in the study that cluster below 6 or 40, respectively, are assumed to be similar. The repeated samples were also added to just the Dimlington samples, and z-scores calculated. The repeated samples were again clustered using these z-scores (Figure 3.2) and identified a level of dissimilarity of just over 5 (Euclidean distance) and 30 (squared Euclidean distance) for clustering the Dimlington samples based on individual z-scores.

Cluster analysis was also performed on all the Dimlington samples, including the repeated samples. Using the complete linkage method, cluster dendrograms from combined and individual z-scores show four out of the five repeated samples clustering together, where only sample D5.12e clusters in a very different cluster group to the rest. Both Ward's method cluster dendrograms cluster three of the repeated samples together, and the remaining two cluster with these three at a very low dissimilarity level.

Therefore although the standard deviations for the repeated samples are high and indicate variation between the repeated samples, the variation between them is not as great as between other samples. Consequently, the sampling technique used for the geochemical analysis produces results that can be assumed to be representative of the bulk sample, and that can be used to reliably distinguish groups of similar samples using cluster analysis.

Sample ID	Na	Mg	Al	Si	K	Ca	Ti	Fe	P
D5.12a	4519.54	4313.89	30665.10	215111.73	17022.86	30052.55	3335.89	30020.60	654.44
D5.12b	3735.98	3697.29	28490.06	191130.31	16179.07	29342.01	3245.86	28991.02	917.84
D5.12c	3848.33	5093.24	36392.71	211335.68	16588.77	27825.55	3374.06	28589.66	1344.78
D5.12d	3286.47	3493.72	28164.68	192330.83	15482.71	28759.79	3227.12	28536.02	1943.68
D5.12e	4848.31	4530.05	31754.99	216238.04	18863.37	34257.21	3641.41	32041.19	1035.74
SD	628.49	645.77	3318.83	12462.89	1271.70	2490.72	166.23	1470.85	493.99

Li	Be	B	V	Cr	Mn	Co	Ni	Cu	Zn	As	Se	Zr	Nb	Mo
65.28	1.96	77.66	83.43	87.04	456.29	11.72	36.37	19.44	73.34	11.84	2.37	127.89	11.64	1.24
57.25	1.53	57.29	70.93	72.00	435.04	10.16	30.40	15.91	89.48	10.35	1.41	106.62	9.71	0.98
56.91	1.59	61.55	69.89	74.75	346.91	9.91	29.36	17.54	66.74	12.25	0.88	111.24	9.95	1.02
62.30	1.73	66.38	77.91	82.96	404.91	10.72	32.33	19.52	58.73	9.57	0.23	117.60	10.59	1.24
78.87	2.06	84.51	97.20	98.08	541.33	13.53	40.88	25.34	83.67	10.19	1.95	149.89	13.41	1.39
8.96	0.23	11.34	11.14	10.40	71.43	1.47	4.75	3.56	12.44	1.15	0.85	17.19	1.51	0.17

Ag	Cd	Sn	Sb	Ga	Rb	Sr	Y	Ce	Nd	Pb	Bi	Tl	Th	U	Ba
0.38	6.36	2.67	0.66	24.45	55.97	223.84	7.83	39.31	12.59	16.54	0.07	0.50	4.02	2.21	284.21
0.31	6.79	1.46	0.51	20.82	54.15	195.76	6.50	34.04	11.13	13.98	0.09	0.44	3.31	1.81	248.77
0.29	6.81	1.31	0.53	21.25	39.30	176.24	7.81	34.66	10.73	14.08	0.05	0.42	4.01	1.78	256.75
0.78	6.24	1.70	0.57	23.24	50.64	204.87	7.15	35.61	11.22	16.28	0.39	0.44	3.64	2.02	275.13
0.54	0.63	3.26	0.75	27.13	57.05	249.79	7.98	42.38	13.89	18.98	0.17	0.56	4.05	2.42	310.66
0.20	2.66	0.85	0.10	2.56	7.20	28.03	0.62	3.55	1.31	2.06	0.14	0.06	0.32	0.27	24.38

Table 3.1. Standard deviations associated with element abundances for the repeated sample D5.12.

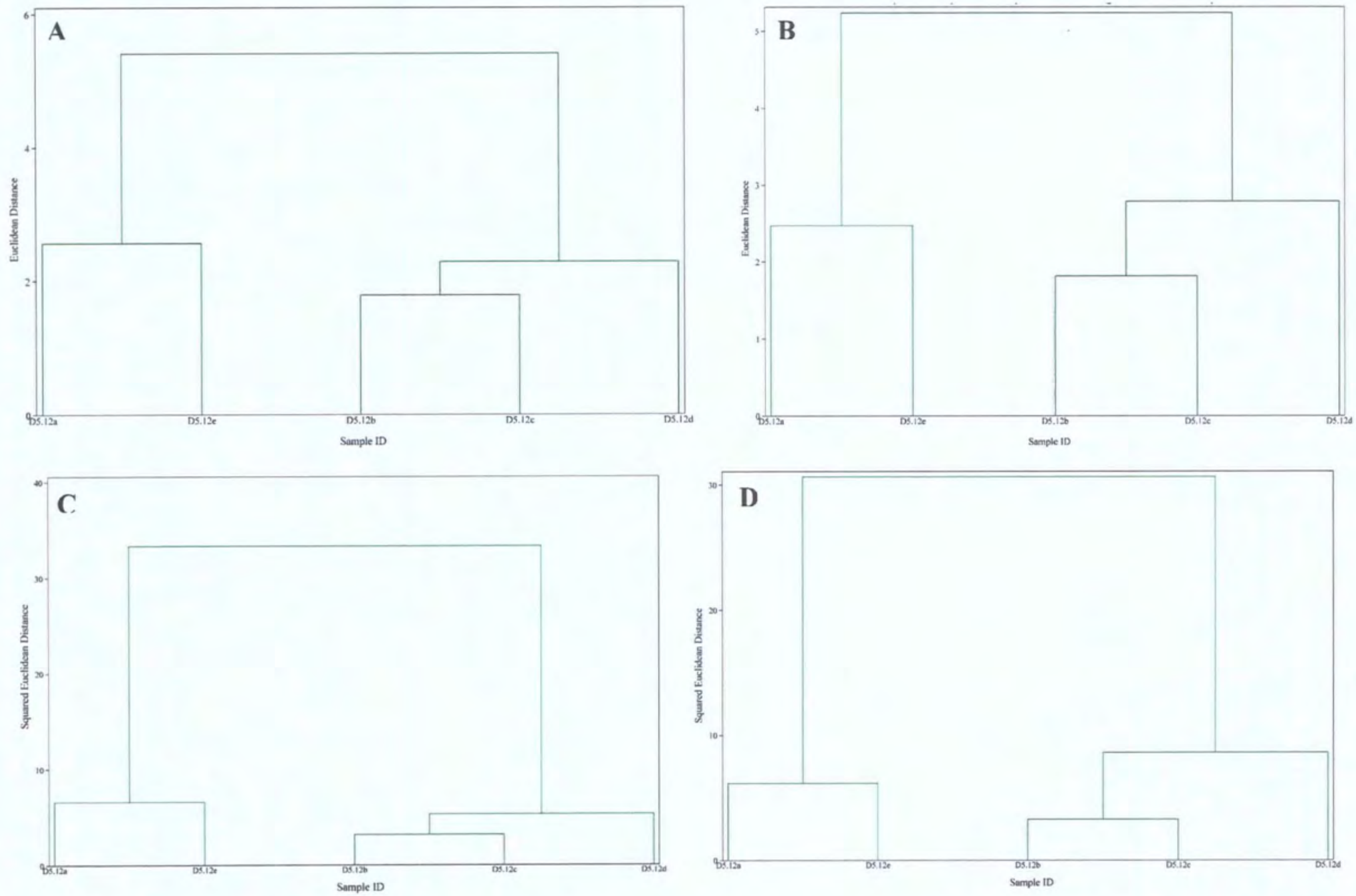
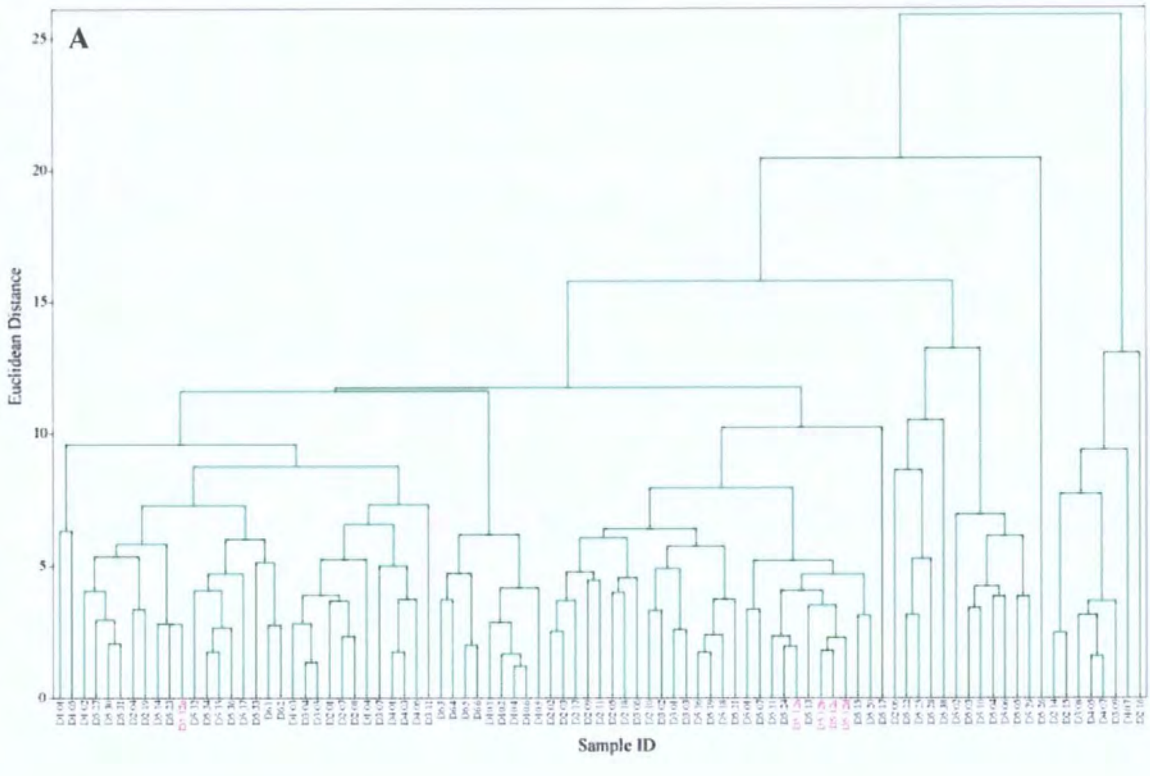


Figure 3.1. Cluster dendrograms of D5.12 repeated samples, using A) Complete linkage, combined z-scores, B) Complete linkage, individual z-scores, C) Ward's method, combined z-scores, D) Ward's method, individual z-scores.



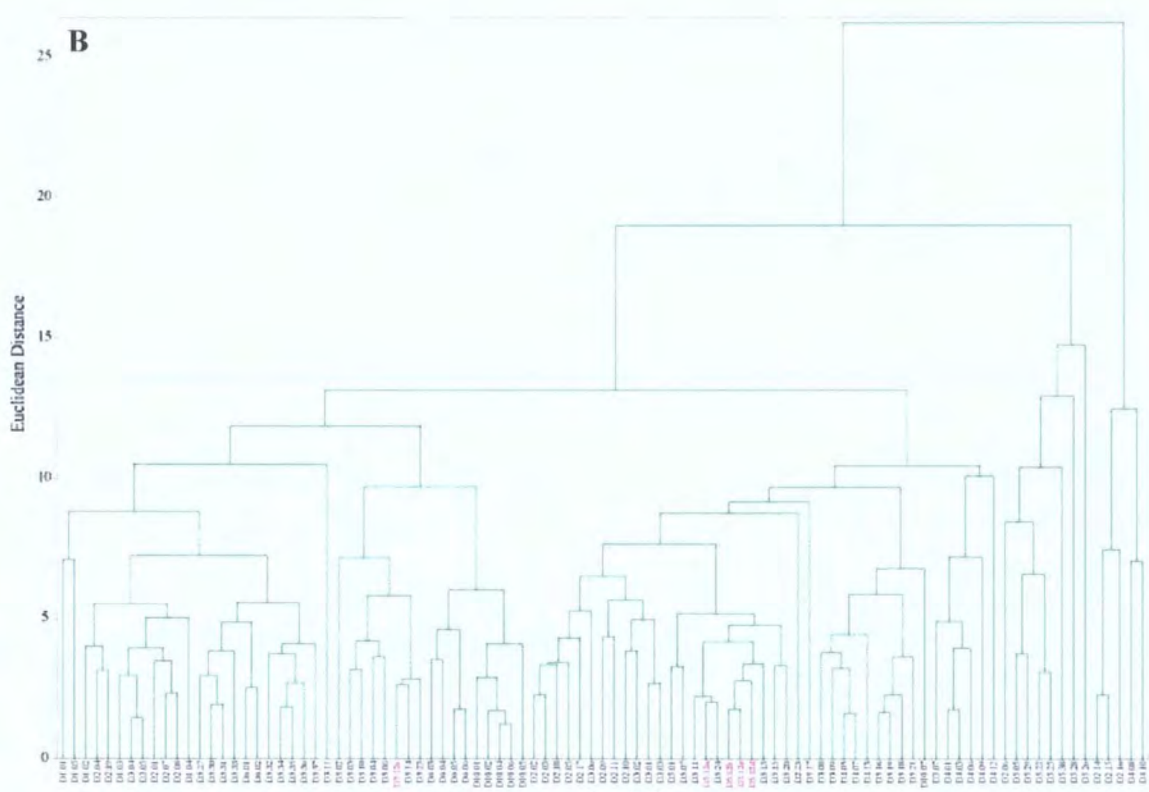
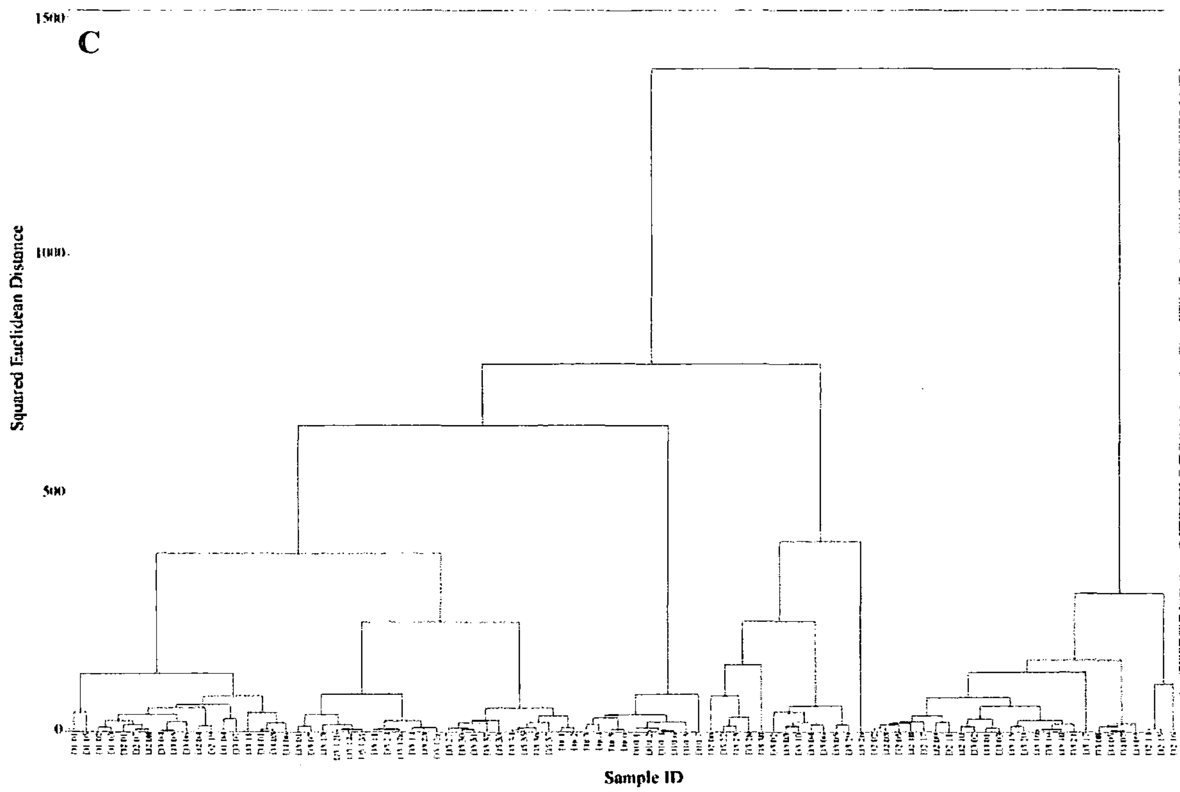


Figure 3.2. Cluster dendrograms of D5.12 repeated samples (marked in red) with all Dimlington diamicton samples, using A) Complete linkage, combined z-scores, B) Complete linkage, individual z-scores, C) Ward's method, combined z-scores, D) Ward's method, individual z-scores.



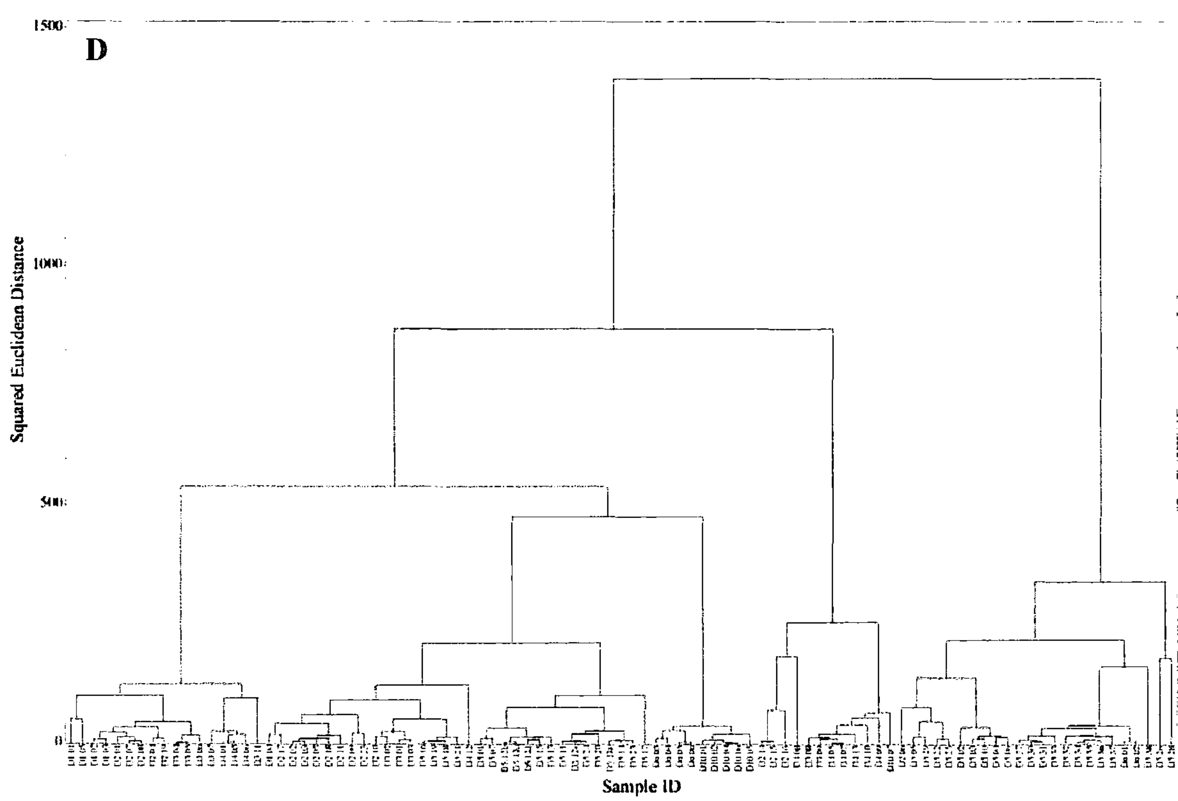


Figure 3.2. *continued.*

Laboratory Error

Table 3.2 shows the minimum and maximum errors associated with the ICP-MS Total Metals Extraction method. All high abundance elements, except phosphorus (P) show reasonable percentage errors; maximum errors are around 7% or lower and the medians are no more then 2.2%. Phosphorous is unreliable due to molecular interferences. EPA Method 200.8r5.4 uses nitric acid (*cf.* Section 3.2.2), and ions such as NOH^+, NNH^+ and NO^+ may have interfered with the detection of phosphorus ions. A number of low abundance elements also show very high percentage errors. These errors mainly occur for elements where the abundance drops below 1ppm in particular samples. The higher uncertainty at low abundances is due to the insensitivity of the ICP-MS machine at these low levels.

The elements with high errors due to very low abundances are Be, As, Se, Mo, Ag, Cd, Sn, Sb, Y, Ce, Nd, Bi, Tl, Th, U. Most of these elements, apart from thallium (Tl), also have higher abundances in other samples, which produce much smaller percentage errors. This is shown by the much smaller median percentage errors for these elements, some of which are below 10%. To not include these elements in the cluster analysis due to the large percentage errors in a relatively small number of results could potentially bias the cluster analysis results in favour of the more abundant elements. This may lead to the omission of critical trace elements. For example, abundances for Se and Ce range from 0 to 40 or 60 ppm, therefore even when errors of around 0.2 ppm for low abundances are taken into account, the change in abundance between the low and high abundance samples is still significant. Therefore it may be unhelpful to remove elements like these based on their high percentage errors. However, elements such as Tl, have much smaller ranges and therefore changes in abundance between samples may not be as much as the error associated with them. The abundances are, however, so low that they are unlikely to significantly affect the results of the cluster analysis. However samples or groups of samples will not be compared in terms of their abundances of these high error elements, nor will they be used in comparisons between abundances of one element and another.

Element	Min % Error	Max % Error	Median
Na	0.20	4.13	1.57
Mg	0.12	7.56	2.11
Al	0.04	7.08	1.14
Si	0.02	2.01	0.70
K	0.05	2.75	1.14
Ca	0.02	5.78	1.72
Ti	0.15	7.80	1.76
Fe	0.04	5.50	1.51
P	0.40	200.41	15.96
Li	0.33	5.57	1.77
Be	6.69	990.33	14.97
B	0.32	12.38	2.94
V	0.29	4.48	1.68
Cr	0.22	5.44	1.83
Mn	0.06	3.53	0.86
Co	1.36	11.91	3.34
Ni	0.63	9.53	2.96
Cu	0.95	6.84	2.86
Zn	0.23	11.26	2.33
As	1.78	93.44	7.61
Se	1.56	3462.73	50.48
Zr	0.22	11.90	1.58
Nb	1.13	15.21	3.10
Mo	8.99	67.55	21.76
Ag	9.81	315.98	40.37
Cd	2.20	381.41	10.53
Sn	5.14	37.71	14.00
Sb	3.07	134.86	33.68
Ga	0.73	7.83	2.43
Rb	0.43	9.30	2.14
Sr	0.07	3.01	1.01
Y	1.64	1603.81	7.10
Ce	0.52	310.94	1.86
Nd	1.47	5014.06	7.92
Pb	0.29	6.74	2.23
Bi	9.77	536.42	101.43
Tl	25.46	2879.88	49.09
Th	2.50	1154.70	10.05
U	6.36	29.20	10.50
Ba	0.09	3.44	0.94

Table 3.2. Laboratory errors associated with ICP-MS Total Metals Extraction technique.

3.5.2 Particle Size Analysis

Sampling Error

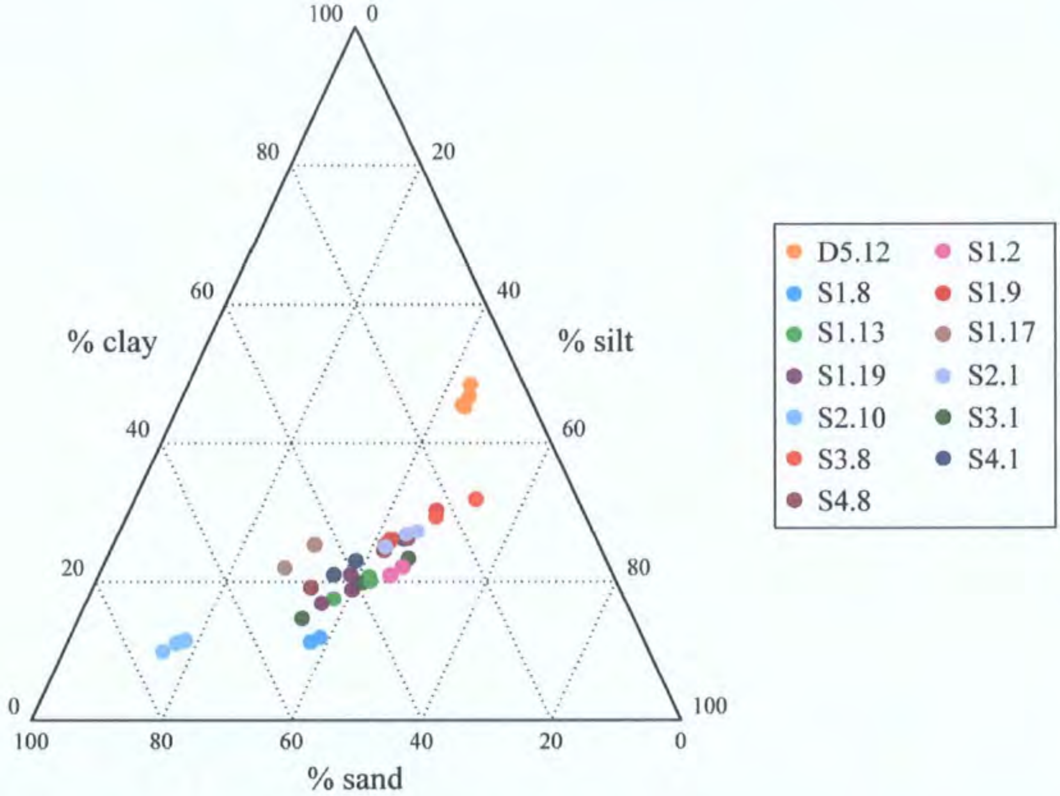


Figure 3.3. Particle size distributions of repeated samples.

A number of samples were repeated to assess the accuracy and precision of the sampling procedure. To evaluate the method of sampling used for all locations except Skipsea (*cf.* Section 3.4), sample D5.12 was analysed four times. Results in Figure 3.3 show that all four percentages of clay, silt and sand are similar. In addition, to test the sampling procedure for clays and sands a repeat sample was taken from S1.8 (clay) and S1.17 (sand). S1.8 produced very similar results again, whilst there were larger differences between the two samples for S1.17. From these results it is assumed that removing a small portion of the bulk sample matrix is a representative way of sampling for clays and diamictons, given time restraints, but samples containing coarser material could have been more accurately selected using a riffle box. However, greater differences in the results for samples containing coarser grains could be accounted for by a lower precision of the coulter granulometer at larger grain sizes, as discussed later in this section.

At the time of sampling, the accuracy of the method of sampling used for the Skipsea diamicton and gravel samples was uncertain, and therefore three repeated samples were carried out for ten samples. Results are also shown in Figure 3.3. Although some repeated samples appear very similar, there is a large amount of variation between others. For this reason, particle size results for Skipsea will be treated more cautiously in subsequent discussions. However, the results are still valuable. Figure 3.4 shows particle size distributions for diamicton units at Skipsea with and without the repeated samples. Although there are some differences, overall there is little change to the clustering pattern of samples from each unit, especially in comparison to particle size distributions from other sites.

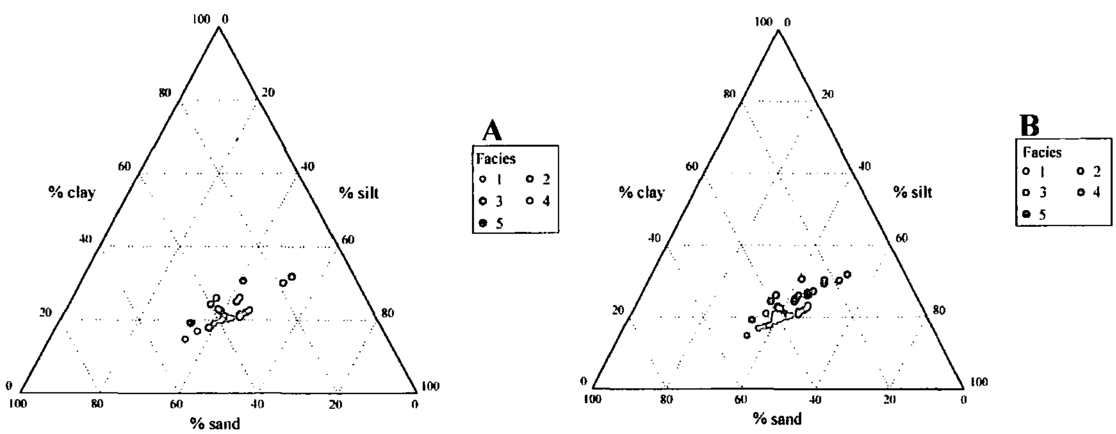


Figure 3.4. Particle size distributions of Skipsea diamictons and repeated samples by facies, A) without repeated samples, B) with repeated samples.

Laboratory Error

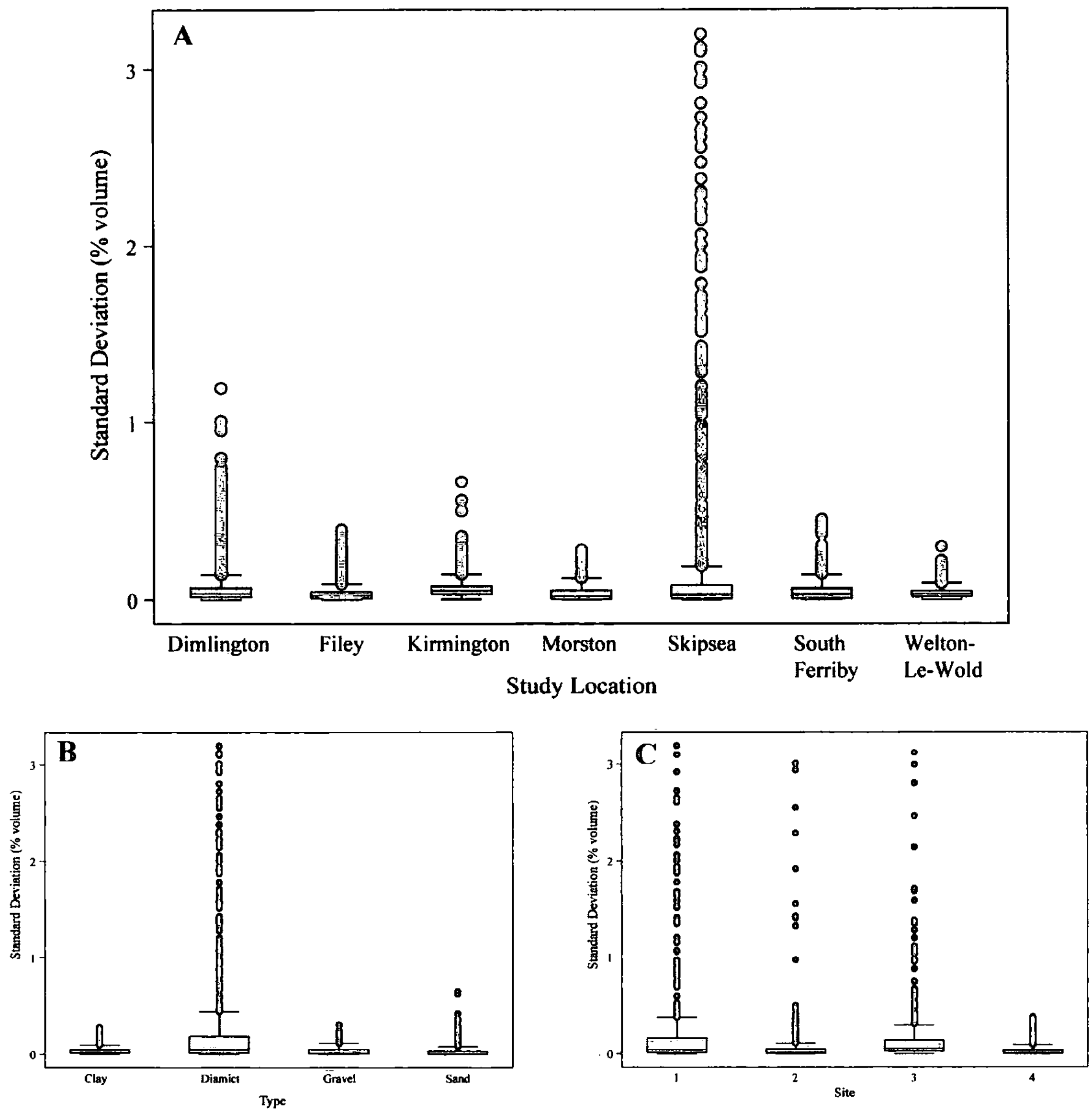


Figure 3.5. Standard deviations associated with repeated coulter runs, A) by location, B) by sediment type at Skipsea, C) by site at Skipsea.

As discussed in Section 3.4, particle size results from the coulter granulometer are the average of two or more runs. Standard deviations were calculated for % volume of each particle diameter interval produced by the coulter. Figure 3.5 shows the range of standard deviations for all samples at each site. In general standard deviations for most sites are below 0.5 % volume and most are very close to zero, indicating that the coulter granulometer was able to precisely replicate results. However, some results for Skipsea produced much larger errors of up to 3.2 % volume. Most diameter intervals have % volumes of 3 or less, and therefore this is a significant error. Further investigation shows that these high standard deviations occurred within the diamicton samples and across Sites 1 to 3 (Figure 3.5). They also mainly occurred in the grain size range 36.24

– 110.99μm where in fact % volumes are generally higher (up to 7% of total volume), thus decreasing the significance of this error slightly. Nonetheless, there are still large differences between individual runs within the Skipsea data. This is highlighted by the fact that Skipsea was the only location where an average of six runs needed to be taken for some samples due to none of the paired runs being similar enough. Dimlington samples also contained some larger differences, where often the third and fourth runs were averaged, compared to smaller standard deviations at locations where the first and second runs were very similar. Coulter precision problems may be due to a number of factors, but significantly, all the Skipsea and some of the Dimlington samples were analysed when the water temperature going into the machine was very low, due to winter temperatures outside. This is likely to have had a significant effect on the machine. However, it is unclear why it would affect diamicton samples only, perhaps due to the larger range of grain sizes present. In general the largest differences between the two coulter runs did tend to occur in the larger grain size range (see Figure 3.6), and standard deviations were overall higher in this area. This indicates that the coulter granulometer may become less precise (and potentially inaccurate) as particle diameter increases.

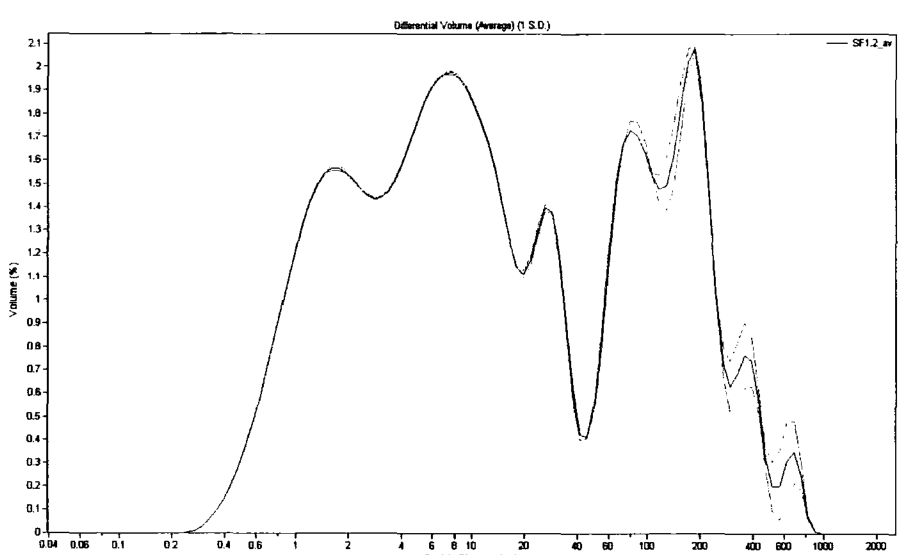


Figure 3.6. Particle size distribution of sample SF1.2 including limits (in orange) to 1 S.D. The distribution curve and its limits are typical of a large proportion of particle size distributions in this study.

3.6 Summary

Field Methods: Sections were logged and lithofacies identified according to structural characteristics. Sampling took place along vertical transects at 0.5m intervals for geochemical analysis and every 1m for particle size analysis.

Geochemical Analysis: The strategy used for the selection, preparation and analysis of the geochemical samples was chosen according to previous geochemical research and four key points were identified. Firstly, whilst the majority of studies in Canada recommend avoiding direct sampling from weathered till, since post-depositional weathering has a significant effect on the composition of tills, the current research collected samples from weathered till in order to assess changes in the composition of the weathered and unweathered samples (e.g. within the Withernsea Till). Secondly, the range of grain sizes used for geochemical investigation has also been argued to have an effect on the range of elements found and therefore, this research chose a broad particle size range of 2mm and under, to avoid biasing the sample towards particular groups of elements. Thirdly, although most geochemical research has investigated regional geochemical patterns, several show the applicability of the technique for investigating changes in till composition upwards in a sequence. Although this research uses this approach, its method differs, as it aims to differentiate stratigraphic groups based upon their geochemical signature rather than comparing pre-defined units. Finally, research in Britain by Burek (198a,b; Burek & Cubitt, 1979, 1991) highlights the applicability of multivariate statistical analysis for analysing geochemical data.

Laboratory and Analytical Methods: Geochemical analysis was undertaken using ICP-MS Total Metals Extraction using EPA method 200.8 r5.4. Results were analysed by hierarchical cluster analysis using both complete linkage and Ward's methods. Samples of grain size less than 2mm were also analysed for particle size using the *Beckman Coulter LS 13 320* Laser Diffraction Particle Size Analyser.

Errors: Geochemical: Standard deviations of geochemical results for repeated samples appeared high indicating some variations between samples. Cluster analysis, however, demonstrated that compared to other samples, the variation between the repeated samples is less significant. Therefore it can be assumed that the sampling technique used produces results that are representative of the bulk sample and that can be reliably used to differentiate groups of geochemically similar samples. Investigation of laboratory errors shows that there are large errors associated with elements with very low abundances. **Particle size:** The assessment of sampling error in particle size analysis demonstrates that most repeated samples produced similar results. However, some differences may have been caused by the accuracy of the sampling method for Skipsea. Investigation of laboratory errors reveals that although most standard deviations are very low, there are some precision problems in the Skipsea and Dimlington data sets and in samples containing a higher proportion of larger grain sizes.

Chapter 4: Results

4.1 Introduction

This chapter is divided into three parts. Section 4.2 'Section Descriptions' provides vertical lithofacies logs, section sketches, annotated photographs and sample locations for the sections investigated at Dimlington, Skipsea, Filey Brigg, South Ferriby, Kirmington, Welton-Le-Wold and Morston and establishes facies associations for the diamicton units found. Lithofacies codes, adapted from Benn and Evans (1998), Eyles *et al.* (1983) and Krüger and Kjaer (2000), were used to describe the physical properties of the sediments found at each site. A key to lithofacies codes used is provided below in Figure 4.1. Lithofacies descriptions were then used to identify facies associations based upon sediment characteristics such as structural characteristics, sediment architecture, sorting, texture and colour. Summaries of each facies association are provided at the end of each site description.

Section 4.3 'Geochemical Analysis' displays and discusses the geochemistry results and uses cluster analysis to determine geochemical groups of similar diamictons, initially at each site, and then compares geochemical signatures between sites (see Appendix ii for graphs of element abundances by site). Section 4.4 'Particle Size Analysis' provides the results of particle size analysis on the fraction of the diamicton matrix below 2mm. These results are discussed in terms of their comparison to lithofacies established in Section 4.2, and geochemical groups established in Section 4.3.

Diamictons	
Dmm	Matrix-supported, massive
Dml	Matrix-supported, laminated
Dmh	Matrix-supported, heterogeneous
Dcm	Clast-supported, massive
---(1)	Clast poor
---(2)	Moderate
---(3)	Clast rich

Gravels	
Gms	Matrix-supported, massive
Gm	Clast-supported, massive
Gh	Horizontally bedded
Glg	Gravel lag

Granules	
GRh	Horizontally bedded
GRms	Matrix-supported, massive
GRp	Cross-bedded

Sands	
Sh	Horizontally/plane bedded or low angle cross-lamination
Sl	Horizontal and draped lamination
Sm	Massive

Silts and Clays	
Fl	Laminated
Fm	Massive

Figure 4.1. Lithofacies codes. Adapted from Benn and Evans (1998), Eyles *et al.* (1983) and Krüger and Kjaer (2000).

4.2 Section Descriptions

4.2.1 Dimlington (TA 398208 – 386223)

The Dimlington cliffs are situated a couple of miles north of the village of Easington, and can be accessed immediately after the Dimlington gas terminal on the coastal road to Holmpton. The coastal sections at Dimlington provide some of the most complex stratigraphy on the east coast of England, where the Basement, Skipsea and Withernsea Tills are all present, as well as inter-beds of sands, silts, clays and gravels. Consequently, eleven sites were studied at this location (Figure 4.2). Sampling took place at Sites 1 to 6 and Site 10, whilst sketches and logs have been produced for Sites 7, 8, 9 and 11, to provide additional information which may be helpful in the analysis of this location.

Site 1 is located at the top of the Dimlington cliffs south of Dimlington High Land (Figures 4.2 & 4.3). The section is 3.5m deep, and the upper 0.5m shows extensive pedogenesis. The diamicton is orange brown (7.5YR 4/2 – 7.5YR 3/4) and extensively weathered with grey streaks providing evidence of gleying. The diamicton is clast rich, although the majority of clasts are less than 8mm in size. Samples D1.1 to D1.5 were taken in this section between depths of 3.5 and 1.5m before the diamicton became too

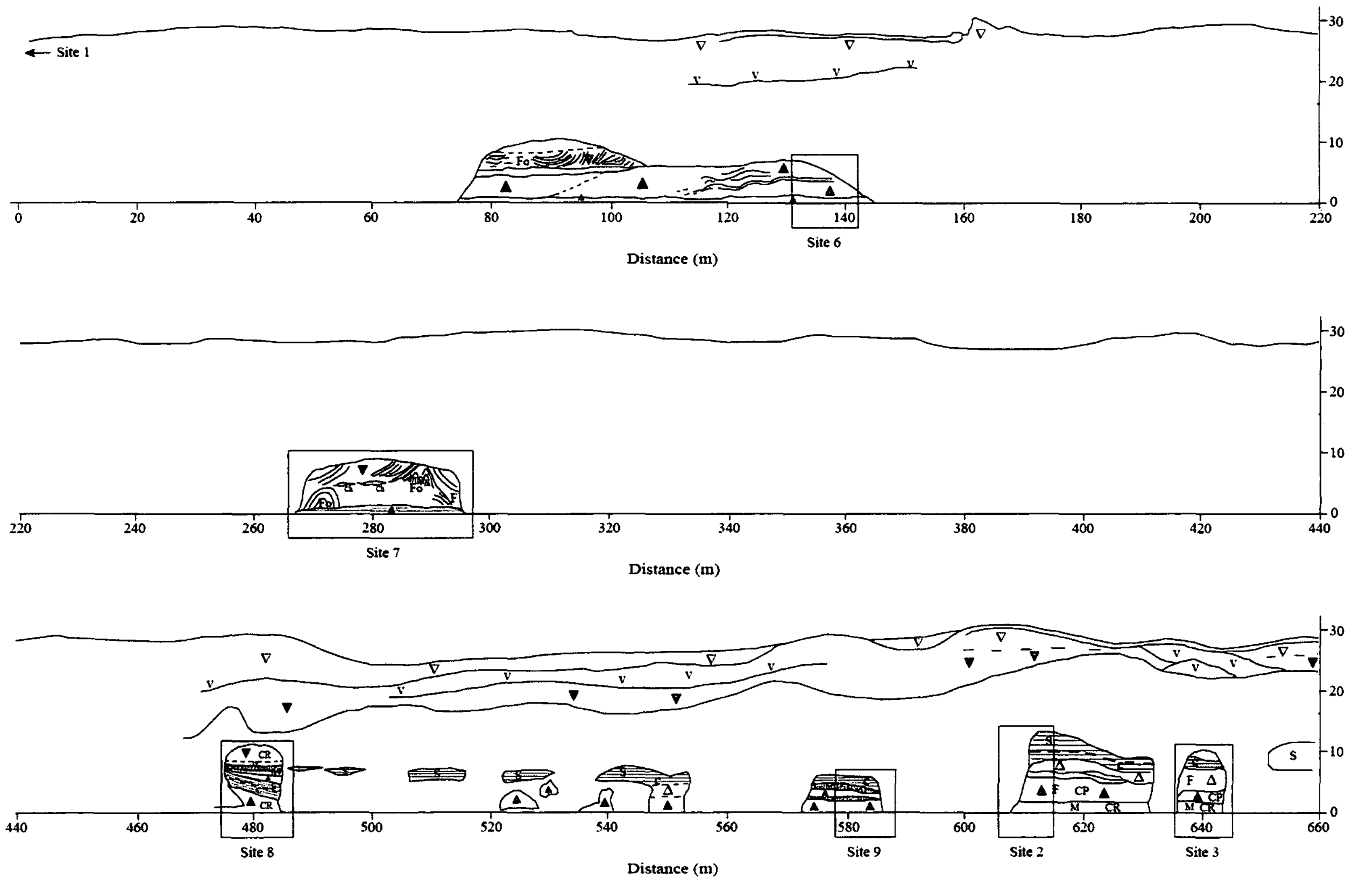


Figure 4.2. Site log, Dimlington, including site locations. Compiled from visits to Dimlington in Nov 2006 and May 2007. Key provided on next page (p.54).

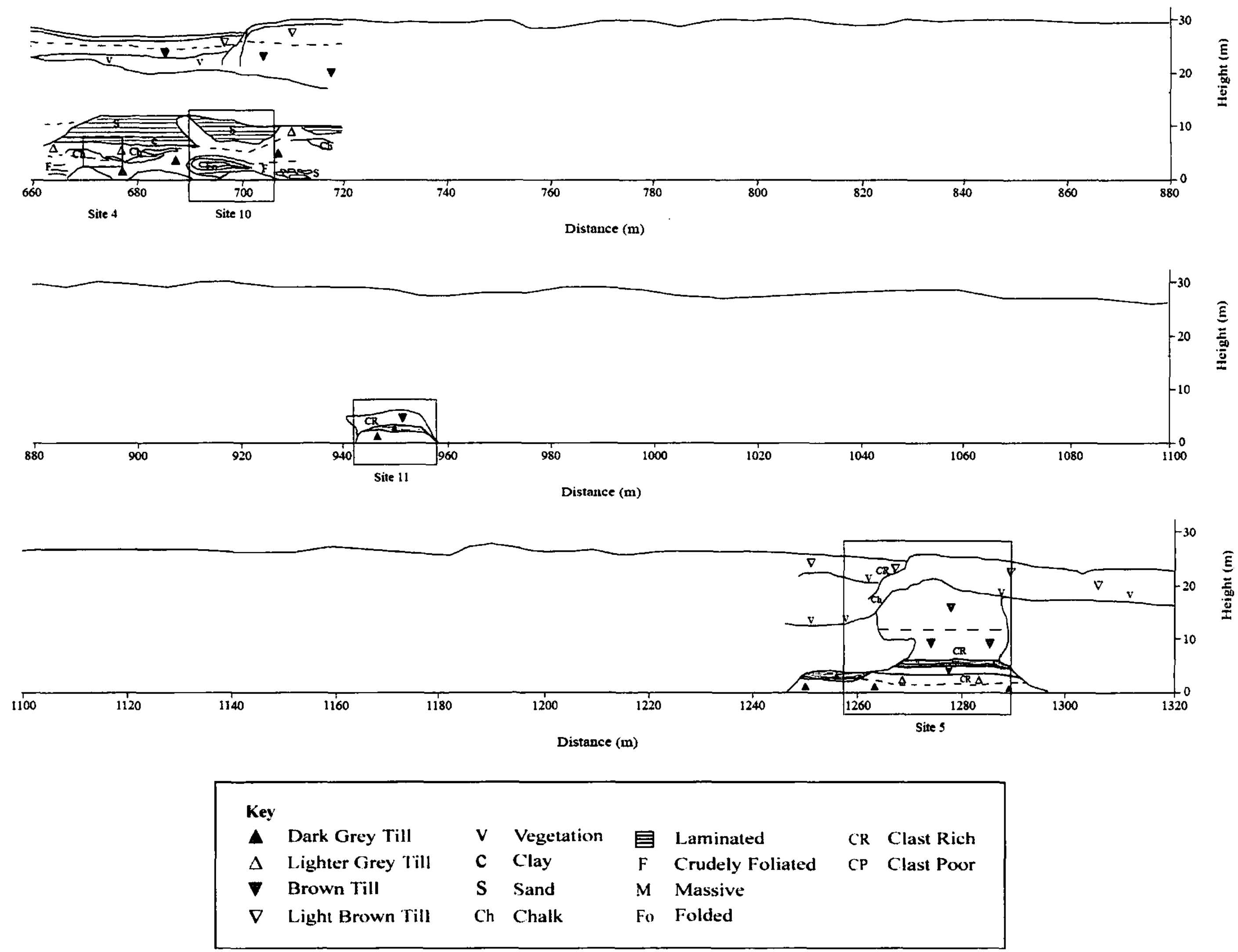


Figure 4.2 *continued.*

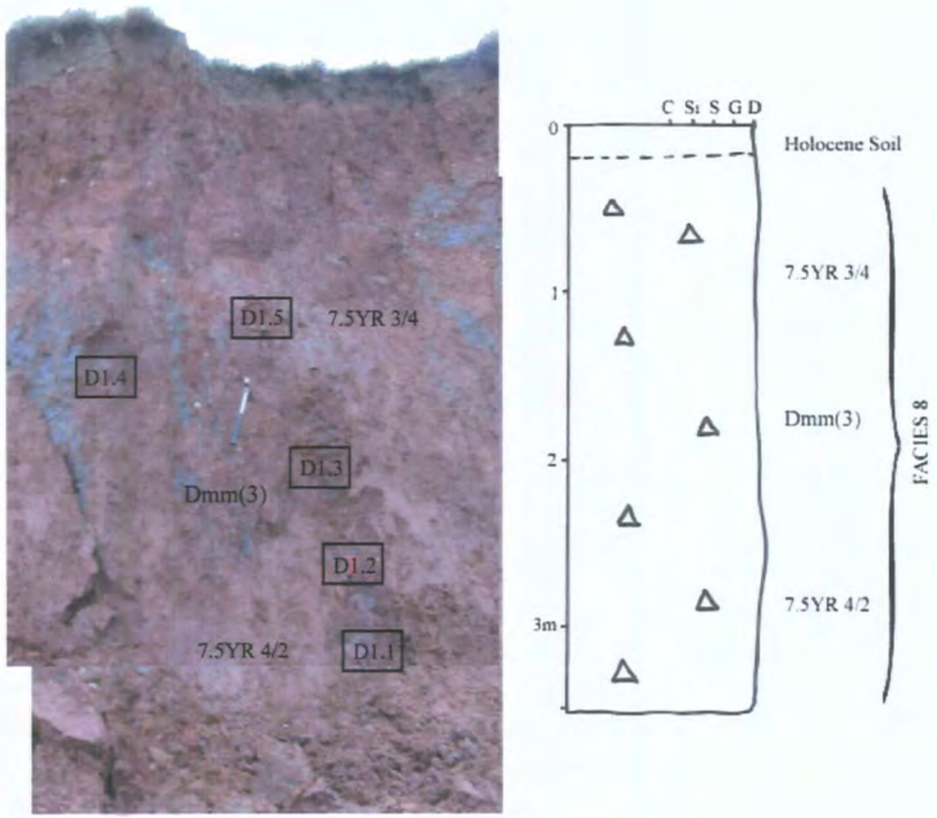


Figure 4.3. Site 1, Dimlington; section log and sample locations. Geological hammer for scale.

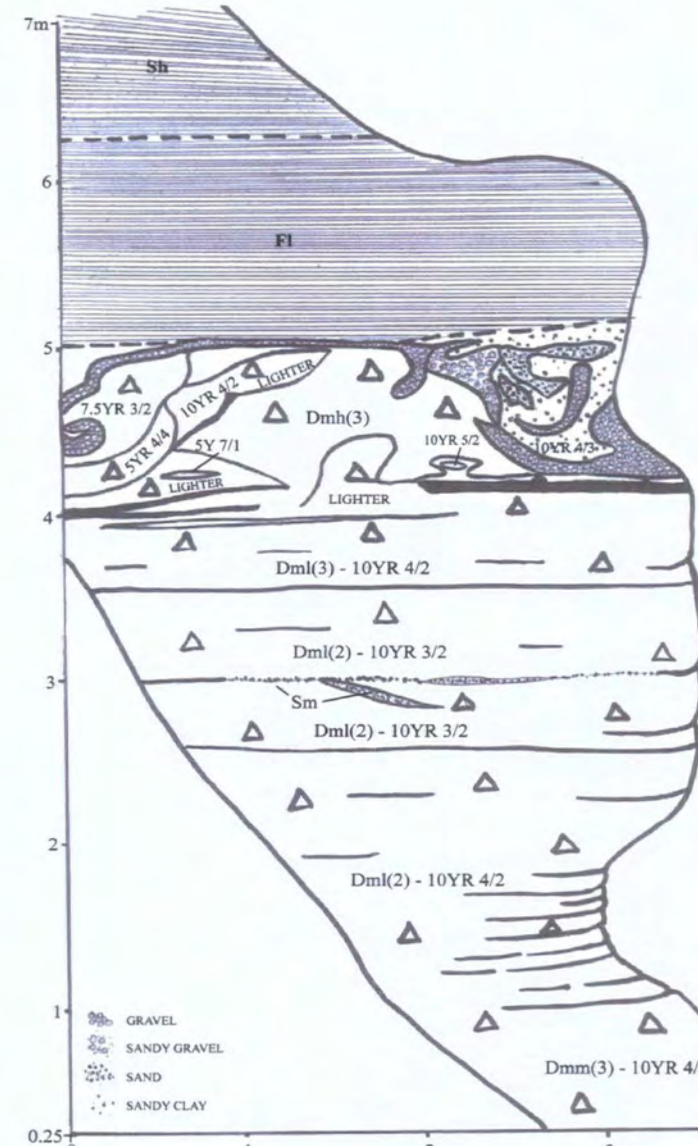


Figure 4.4. Site 2, Dimlington; field sketch.

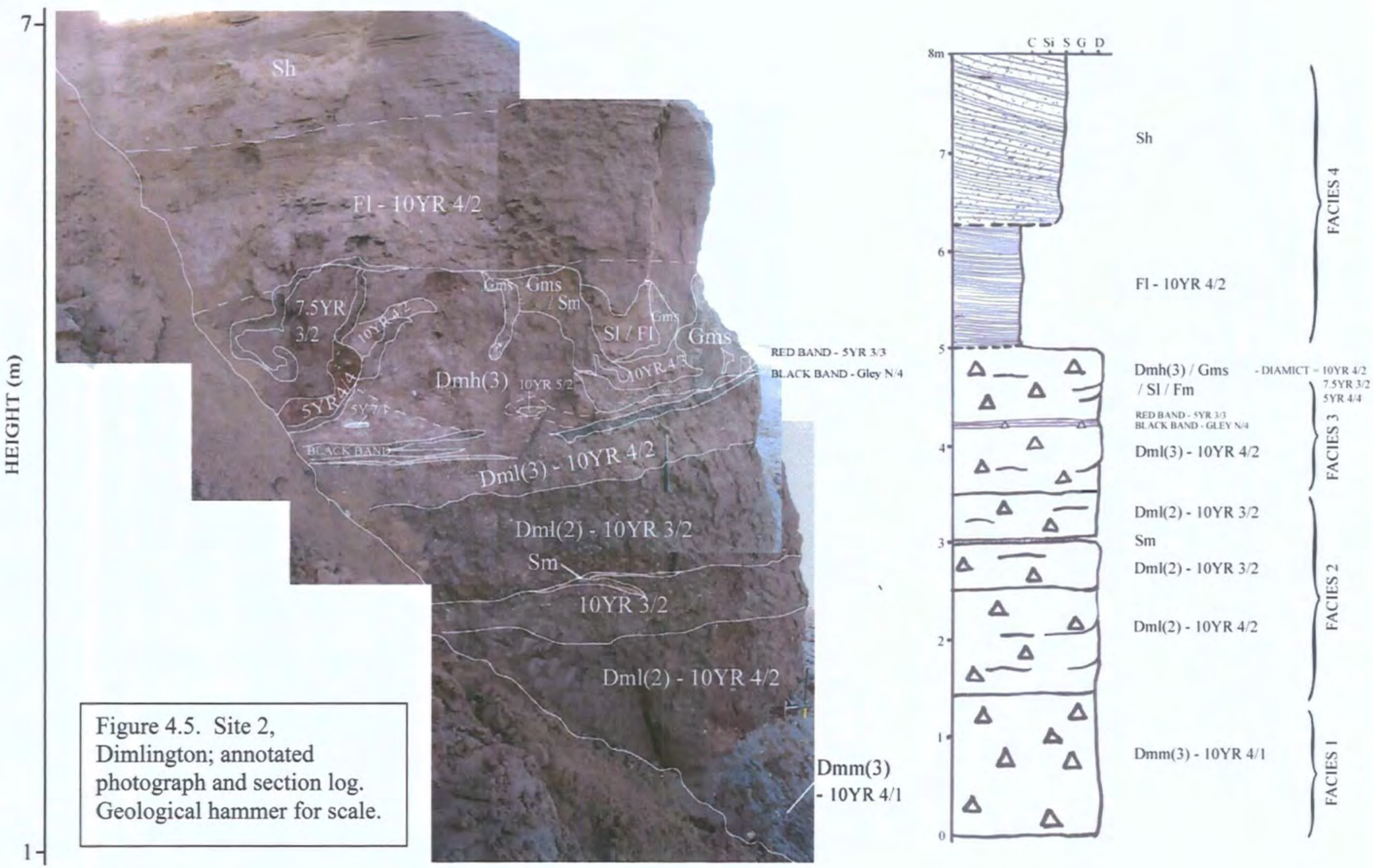


Figure 4.5. Site 2, Dimlington; annotated photograph and section log. Geological hammer for scale.

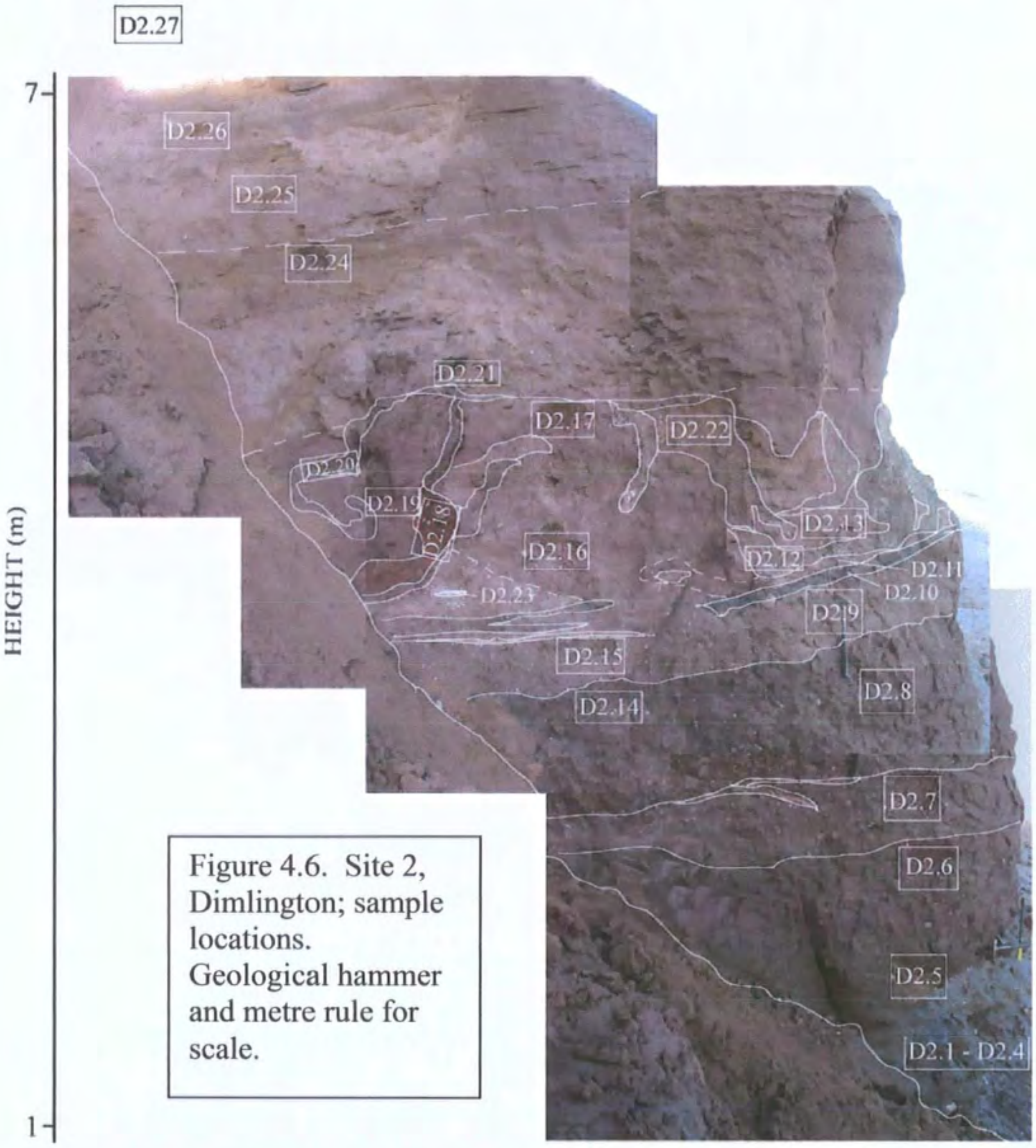


Figure 4.6. Site 2, Dimlington; sample locations. Geological hammer and metre rule for scale.

weathered to be of any analytical value (Figure 4.3). Clasts are predominantly shale and sandstone, as well as a great quantity of red marl and yellow sandstone. Limestone, porphyry and quartz are also present, whilst chalk is only found in the lower, least weathered part of the section.

Site 2 provides an interesting sequence of diamictons below a thick laminated sand unit beneath Dimlington High Land (Figures 4.2, 4.4 & 4.5). Samples were mainly taken upwards along a vertical transect, although some samples were also taken laterally in order to capture all the changes in sediment composition that occurred in this section (Figure 4.6). The lowest unit in this section (Facies 1) is a dark grey (10YR 4/1) massive diamicton, and is predominantly rich in chalk clasts, although the lowest layers contain much less chalk. It is unclear at what depth the unit descends to below the beach, but from beach level upwards, the unit is 1.5m high, and a conformable boundary separates it from a laminated diamicton above (Facies 2).

Facies 2 consists of a number of bands of diamicton, which are differentiated by differences in colour and clast content. Initially, the diamicton in Facies 2 contains less clasts than the Facies 1 diamicton, where the clasts are predominantly shale and sandstone, with some chalk and limestone. The diamicton is also lighter in colour (10YR 4/2). Laminations in Facies 2 are caused by changes in grain size and are accentuated by differential weathering of the coarser material. They are laterally discontinuous, and have concave bases. The first diamicton band is 1m thick and is separated by a conformable boundary with a darker diamicton band (10YR 3/2), which contains more limestone and chalk clasts. A thin, structurally massive, sand lamination runs horizontally midway through this diamicton. In general, it is only a few millimetres thick, but towards the centre of the section it thickens to about 1cm. A lens of massive sand, also about 1cm thick, intrudes into the diamicton below from the sand lamination in the centre of the section. A massive to heterogeneous diamicton (Facies 3) above Facies 2 is significantly lighter (10YR 4/2) and is rich in chalk clasts.

0.7m above the lower boundary of Facies 3, a thin discontinuous grey-black (Gley N/4) diamicton band, 2-3cm thick, containing predominantly shale clasts and virtually no chalk, is followed by a thin band of red diamicton, less than 1cm thick. Above the black band, the diamictons are generally massive in structure, but vary dramatically in colour from very light (10YR 4/2 and 10YR 5/2) to very red (7.5YR 3/2 and 5YR 4/4). The red diamictons occur as near vertical lenses within the more extensive lighter diamicton, where they are separated by sharp boundaries. The lens of very red diamicton (5YR 4/4) is full of clasts and contains a significantly larger proportion of clasts over 16mm (which are predominantly sandstone) than any of the other diamictons. In addition, there is a small pod of very white (5Y 7/1) clay, pinched at either end situated within the light diamicton. Colour varies gradually within the light diamicton body, and clasts within it are mainly shale and sandstone with some chalk.

A discontinuous layer of matrix supported gravels/granules, of mainly shale, rests on top of Facies 3, but also descends within the unit as lenses and pendant structures. The seaward side of Facies 3 is particularly dominated by gravels, where lenses are intermixed with lenses of sandy clay. Where the layer of gravels is not present along the upper boundary, the light coloured diamicton grades into a 1.2m thick unit of horizontally laminated clays (Facies 4). These clays then grade into horizontally bedded sands, where layers of sand occurring in between the clay become progressively denser upwards, until the clay laminations stop entirely. The laminated sand unit continues upwards for at least a 1.5m, after which slumping causes the upper boundary of the sand to be unobservable.

Site 3 is 30m north of Site 2 and contains a similar, yet less complex sequence (Figures 4.2 & 4.7). Facies 1 (dark grey (10YR 3/2), massive diamicton) is visible up to 0.8m above beach level. The diamicton is again clast rich, especially in chalk, and includes a body of massive, lighter (10YR 4/2) diamicton, which is even richer in chalk and limestone than the surrounding diamicton. Above Facies 1, a laminated clast-poor diamicton occurs (Facies 2), containing predominantly shale and sandstone clasts. Here the laminations occur as thick layers of diamicton, 10 – 20cm thick, which fine upwards and are denoted by the erosion of coarser lamina between them. Two diamicton bands occur within Facies 2 at this site, one after 1m and the other after 1.5m. The first is rich in fine small clasts, whilst the second is distinguished by a change in colour to blue-grey (2.5Y 3/2). A thin continuous dark (10YR 3/1) diamicton band separates Facies 2 from a light brown (10YR 4/2) massive diamicton above it (Facies 3). This diamicton is clast-rich, especially in chalk clasts and contains a stringer of chalk, which runs roughly horizontally for about 1m half way up the 1.2m thick section. Unit 3 progressively grades into horizontally laminated clays (Facies 4) of the same colour. These clays reach a maximum thickness of just under 1m before they grade into horizontally

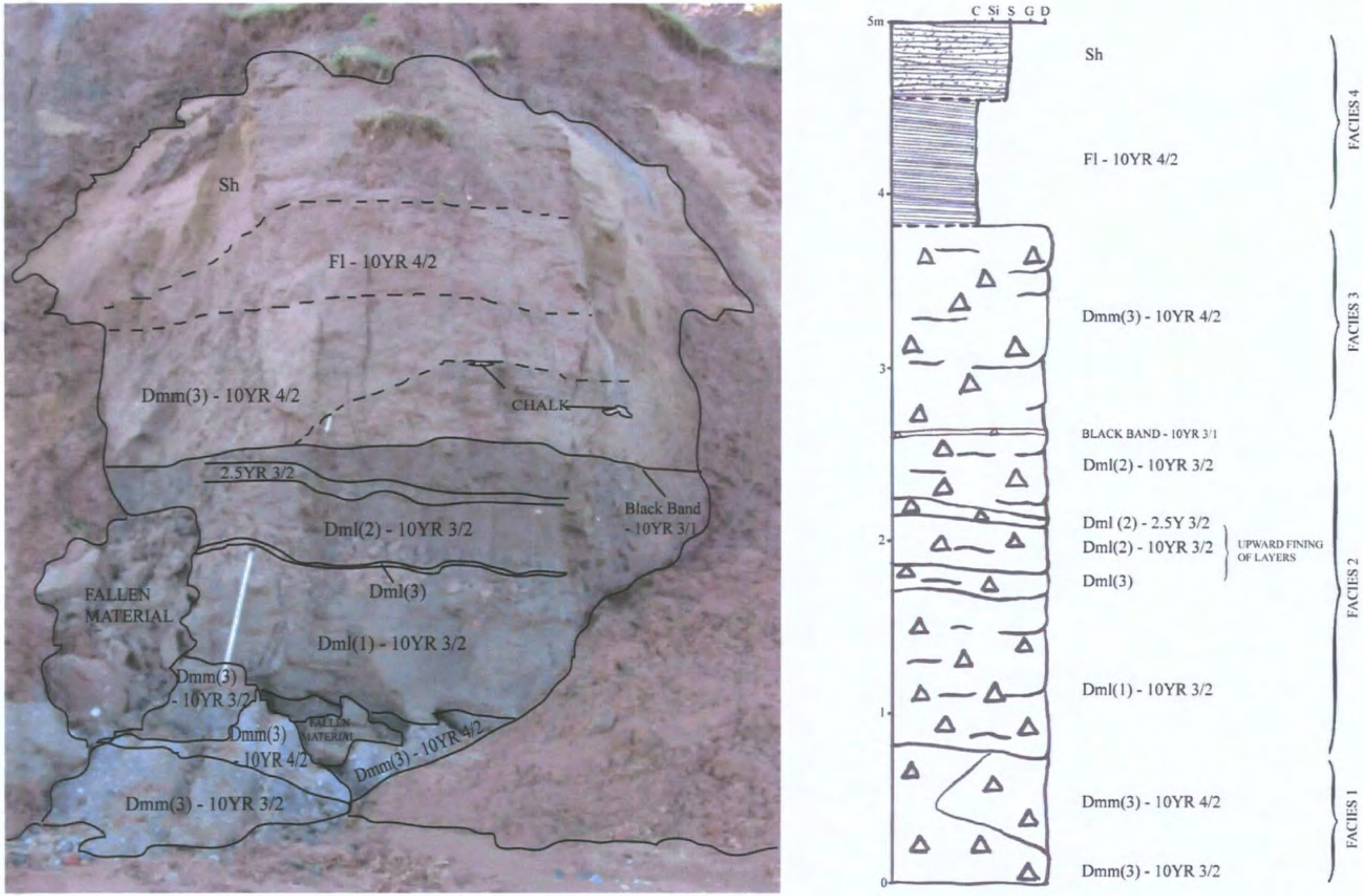


Figure 4.7. Site 3, Dimlington; annotated photograph and section log. Metre rule for scale.

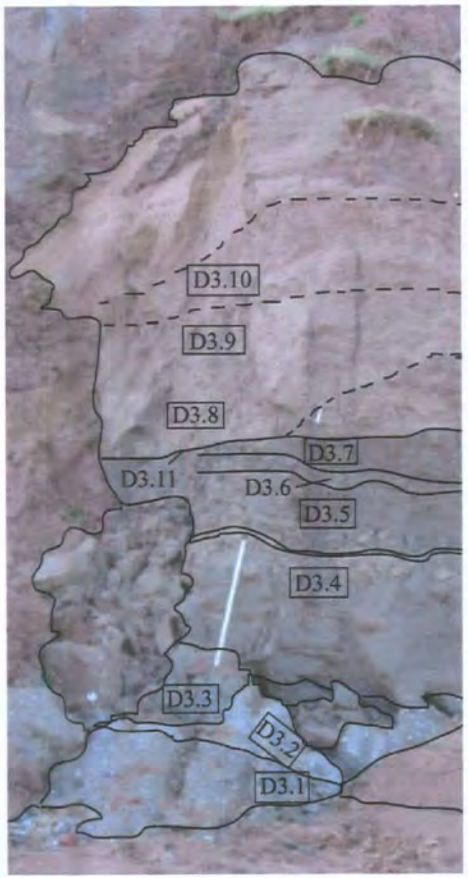


Figure 4.8. Site 3, Dimlington; sample locations. Metre rule for scale.

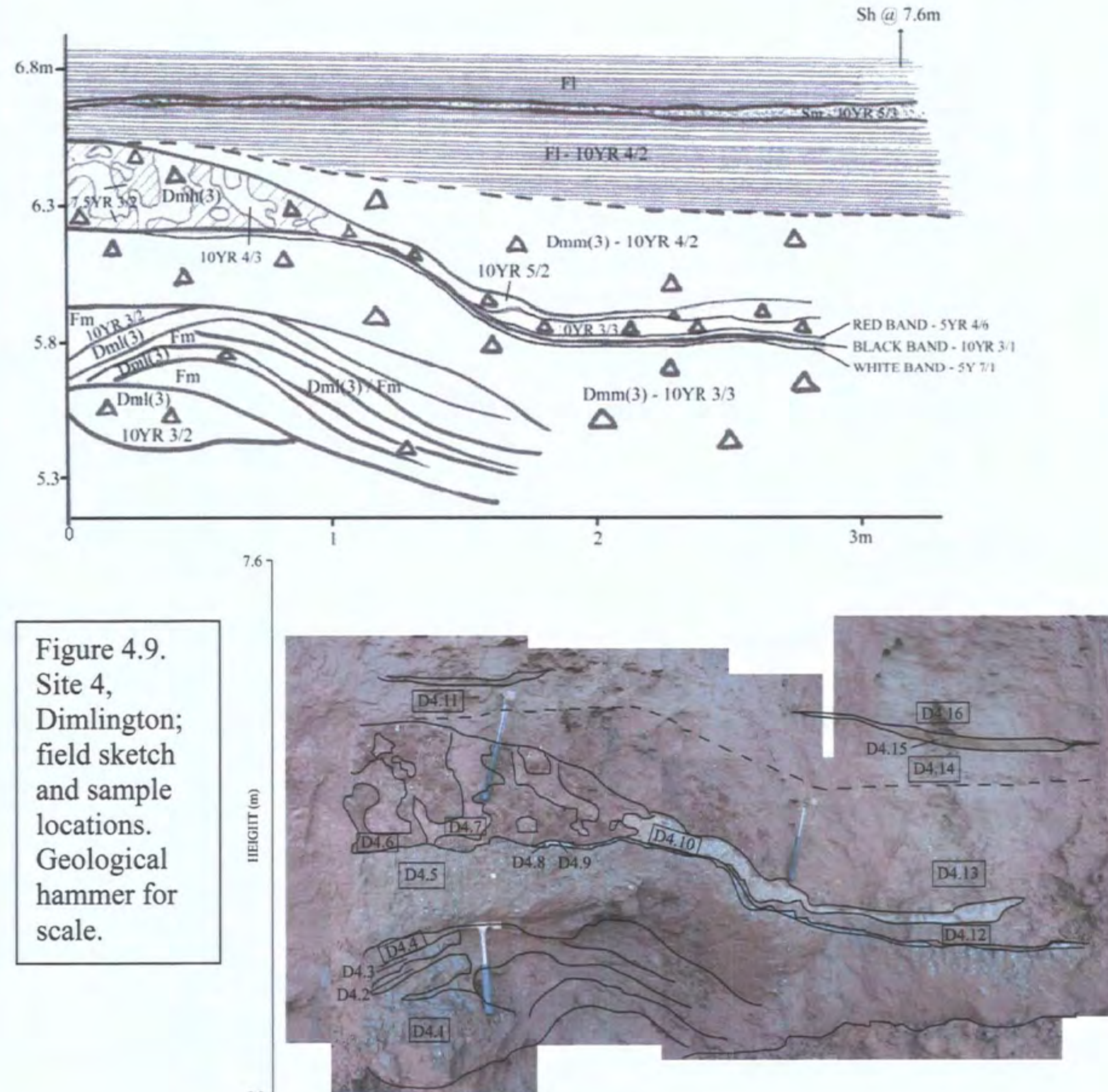


Figure 4.9. Site 4, Dimlington; field sketch and sample locations. Geological hammer for scale.

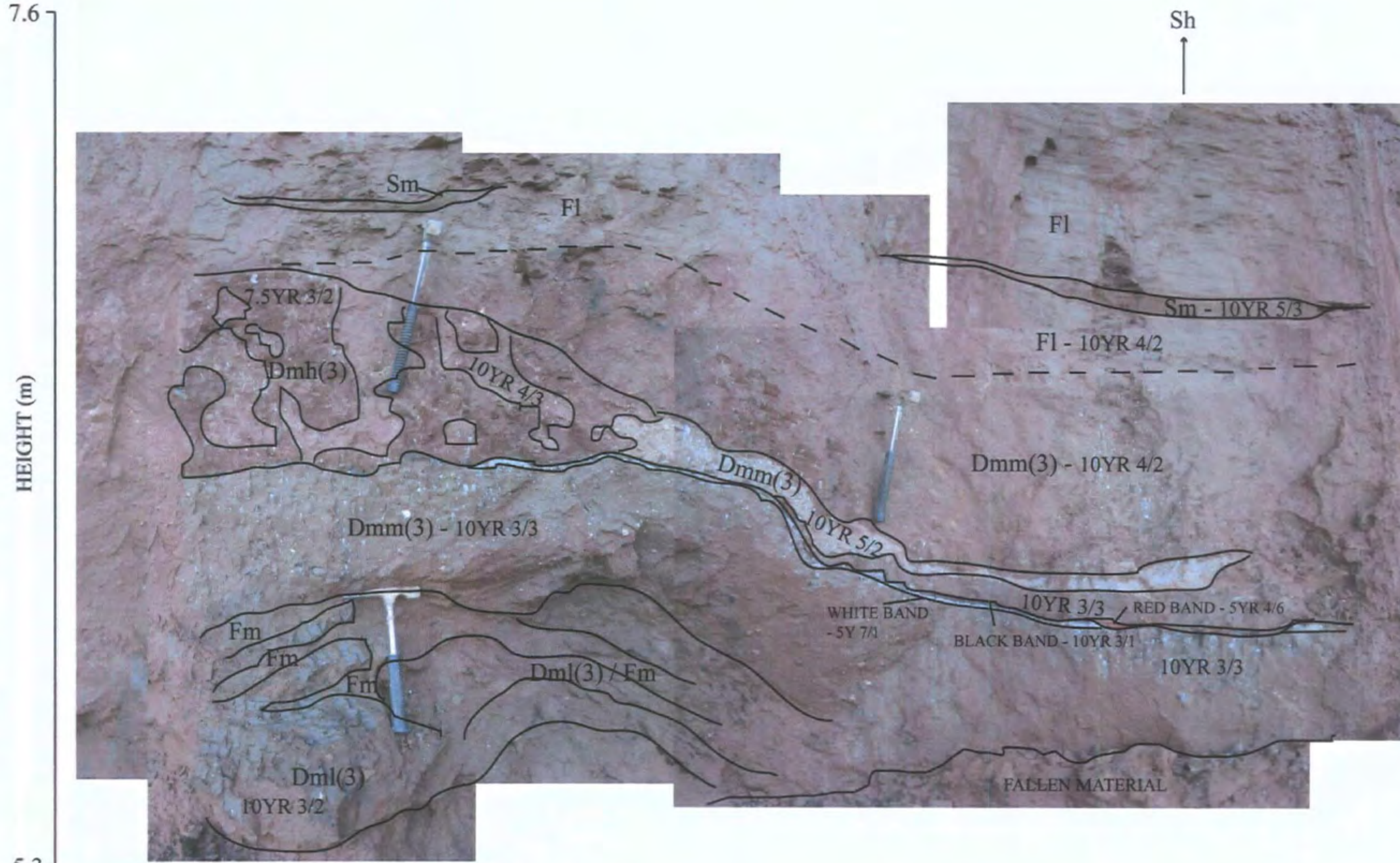


Figure 4.10. Site 4, Dimlington; annotated photograph. Geological hammer for scale.

laminated sands in the same way as those at Site 2. Samples were taken from the three diamicton units and from the laminated clay unit above (Figure 4.7).

Due to a large slump at the base of Site 4, the visible section begins at 5.4m above the beach (Figures 4.9 & 4.10). The lowest unit visible is a dark grey-brown (10YR 3/2) clast-rich diamicton (Facies 2), containing mainly shale and sandstone clasts with very little chalk. This diamicton is discontinuously stratified, where 5-10cm thick diamicton layers are separated by a similar thickness of sandy clay of the same colour. These layers are weakly folded upwards. The visible section of Facies 2 is only 0.3-0.5m thick above which Facies 3 occurs. The lowest band of diamicton in Facies 3 is lighter than Facies 2 (10YR 3/3), much richer in chalk and massively bedded for 0.3m. Between 6.2 and 6.6m above beach level, an area of mixed diamictons occurs, where patches of a light purple (10YR 4/3) diamicton are intermixed with patches of a dark purple-brown (7.5YR 3/2) diamicton. Chalk is present in both diamictons, although there is a slightly higher proportion in the lighter diamicton. At the southern end of the section, it reaches a maximum thickness of 0.55m, whilst it thins northwards towards the underlying diamicton. When it reaches a thickness of 0.15m, it merges into a layer of white chalky diamicton, which contains very few other clasts, and continues thinning to a thickness of 1cm, before swelling out again and stopping abruptly. At this side of the section, laterally discontinuous bands of white and red diamicton lie beneath the white chalk-diamicton layer. The northern end of this layer also intrudes into a layer of light brown (10YR 4/2) clast-rich massive diamicton, containing chalk, shale, sandstone, limestone and quartz, which grades upwards into Facies 4 (laminated clays) at a height of 6.3-6.5m. Laterally discontinuous 4cm thick lenses of sand occur 0.2m above the diamicton/clay boundary. The horizontally-bedded clay laminations begin to grade into horizontally-bedded sand laminations further up the sequence as at Sites 2 and 3, but the actual sand unit is obscured by further slumping above.

Site 5 is the most northerly study site at Dimlington (Figure 4.2), where it was possible to study 21m of vertical cliff section from the beach up to the cliff top. The section is divided into four sub-sections, 5A, 5B, 5C and 5D, which combine to produce a composite log (Figures 4.11-4.14). Samples taken at this site are shown in Figure 4.14. At Site 5A (Figure 4.12), the lowest unit (Facies 5) is a dark grey-brown, laminated diamicton which extends 3m upwards from beach level. Laminations are caused by discontinuous stringers of coarser sediment which have subsequently been preferentially

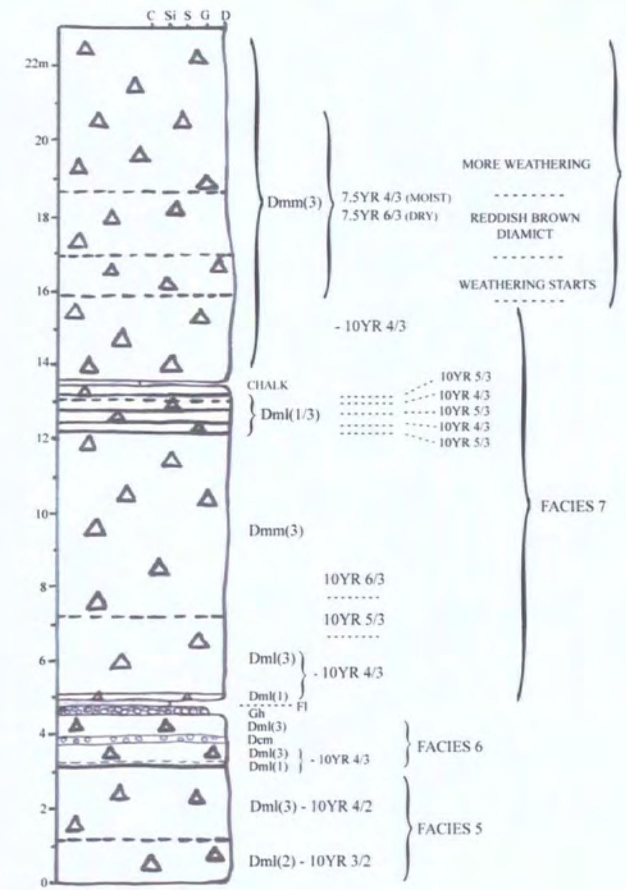


Figure 4.11. Site 5, Dimlington; section log and annotated photograph. Metre rule for scale.

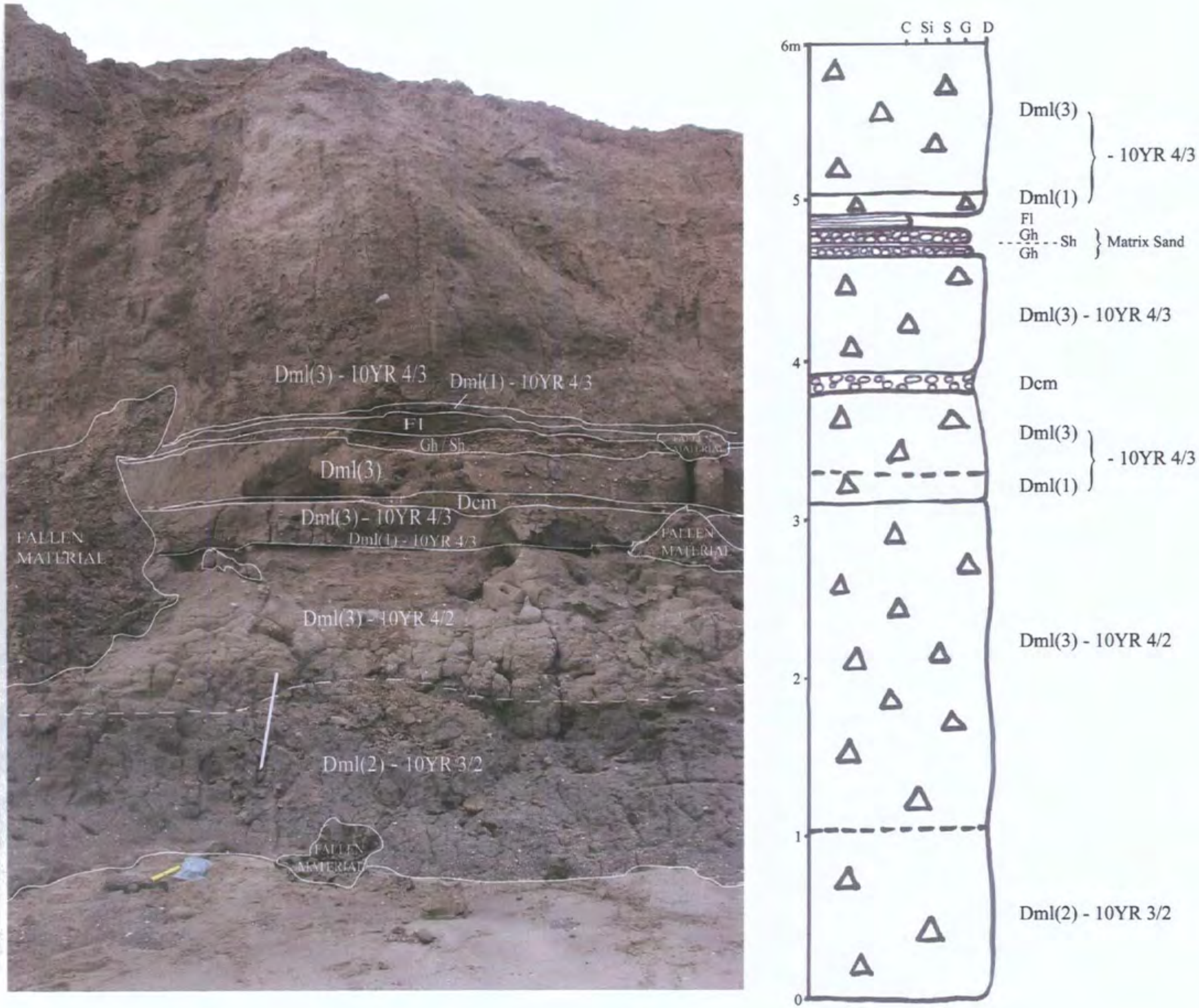


Figure 4.12. Site 5A, Dimlington; annotated photograph and section log. Metre rule for scale.

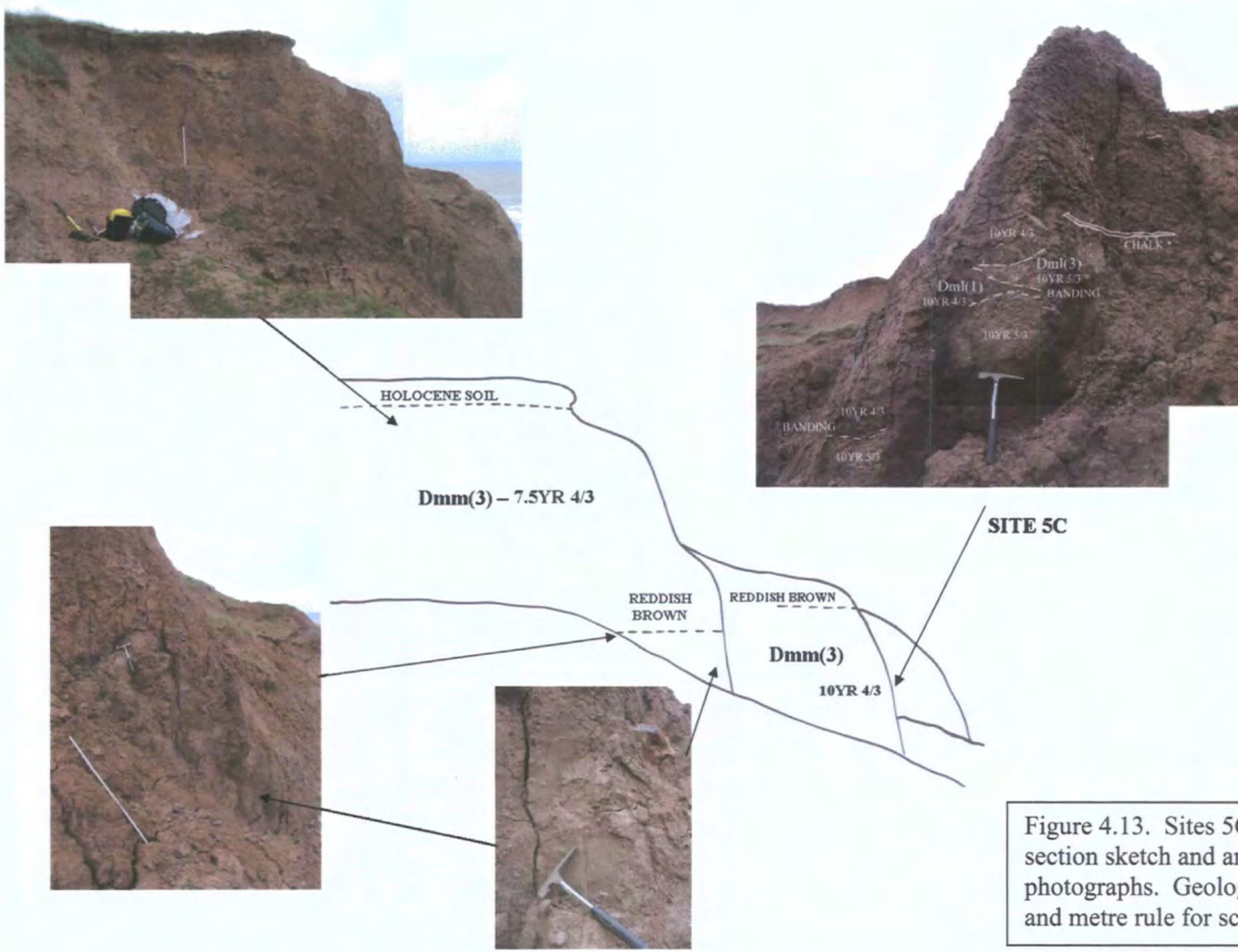


Figure 4.13. Sites 5C and 5D; section sketch and annotated photographs. Geological hammer and metre rule for scale.

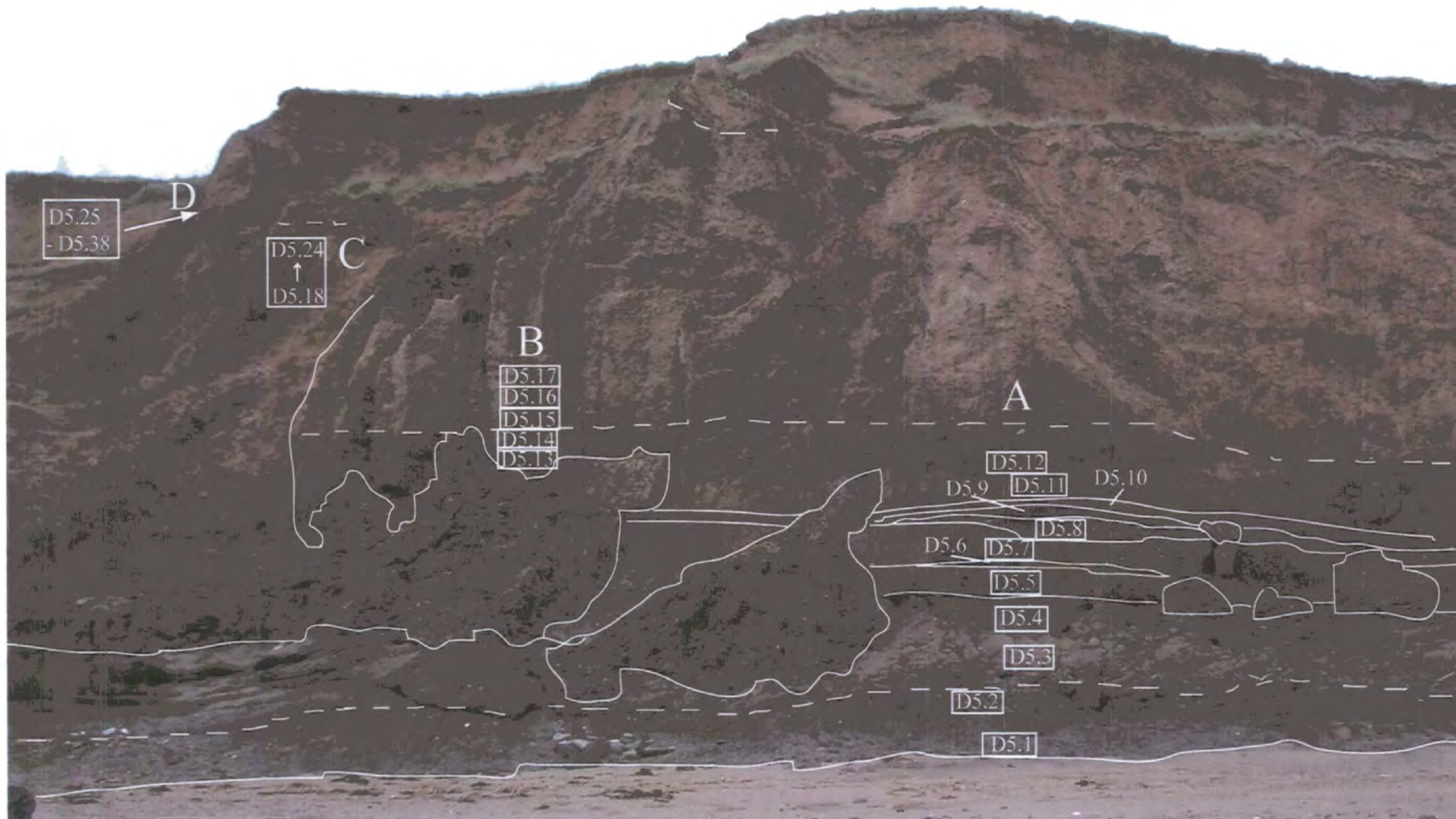


Figure 4.14. Site 5, Dimlington; sample locations.

Figure 4.14 *continued.* Sites 5C (left) and 5D (above), Dimlington. Metre rule and geological hammer for scale.

weathered. It is sub-divided into two sub-units based on a change in colour from 10YR 3/2 to 10YR 4/2. The lower section is within the range of high tide level, and it is therefore possible that the colour change simply represents a difference in moisture content within the unit. However, the upper section is also slightly more clast-rich than the lower section. A sharp boundary divides Facies 5 from the overlying diamicton unit (Facies 6). The laminated diamicton within Facies 6 is distinctly browner (10YR 4/3) than the lower unit. Laminations within this unit occur as subtle changes in matrix colour and possibly also by changes in grain size, although further investigation is required to clarify this. The initial 0.1-0.2m of this diamicton is clast-poor, but the clast concentration rapidly increases upwards and the rest of the 1.6m thick unit is clast-rich. A 0.1-0.15m thick band containing a very high concentration of clasts lies halfway up this diamicton.

Above Facies 6, a 0.2-0.3m unit of gravels occurs, which is supported by a sand matrix, and also divided in half by a thin layer of horizontally laminated sand. Horizontally laminated clays (0.1-0.2m thick) of a darker brown than the under- and overlying diamicton units occurs above the gravels. Immediately above the clays, within Facies 7 lies a 0.2m unit of heavily horizontally laminated diamicton. The diamicton contains few clasts where those present are very small (<4mm). The matrix is very different from the underlying clay, as it is made up of coarser grains and is much more consolidated, resembling that of the overlying diamicton. It is separated from this diamicton by a gradational, yet distinct boundary, where the diamicton becomes clast-rich again. The two diamictons are the same colour (10YR 4/3), but laminations in the upper diamicton become much more diffuse and the unit eventually grades into a massive structure Laminations are again differentiated by subtle changes in colour, although changes in grain size may also be possible. Study of Facies 7 continues at Site 5B (Figure 4.11) where the diamicton becomes lighter from 10YR 4/3 to 10YR 6/3, again due to changes in moisture content within the diamicton. All the diamictons within Facies 5, 6 and 7 contain predominantly shale and sandstone, with some chalk, limestone, flint, porphyry and quartz.

At Site 5C (Figure 4.13), between 12 and 14m above beach level, bands of lighter (10YR 5/3) and darker (10YR 4/3) diamicton occur. Changes in clast concentration also occur within the bands, where the lighter bands contain an increase in clasts especially chalk and limestone. Weathering of the diamicton first begins at around 16m at Site 5D (Figure 4.13), where the diamicton gradually becomes much redder (7.5YR 4/3 wet, 7.5YR 6/3 dry) and less homogenous in colour. The degree of weathering increases upwards to the top of the cliff, where the diamicton at the top (Facies 8) becomes increasingly streaky in colour. Chalk content in this upper section is low, and the diamicton here mainly contains only shale, sandstone and limestone.

Site 6 is located to the south of Dimlington High Land and consists of a 3m section containing two diamictons (Figures 4.2 & 4.15). The lower diamicton (Facies 9) is dark grey (10YR 4/1), massive and clast-poor, and is visible up to 0.5m above beach level. A distinct boundary separates it from the brown (10YR 3/2) diamicton above (Facies 10). This diamicton contains laterally discontinuous laminations caused by changes in grain size and defined by differential weathering of coarser grained laminations. It is clast-rich and, apart from containing slightly more chalk and limestone, has a similar assemblage of clasts to the lower diamicton. A distinct band within the upper diamicton contains a significantly greater proportion of clasts than the rest of the unit and reaches a maximum thickness of just over 0.5m before pinching out at either end. Facies 10 appears to continue upwards, but slumping obscures the section above 3m.

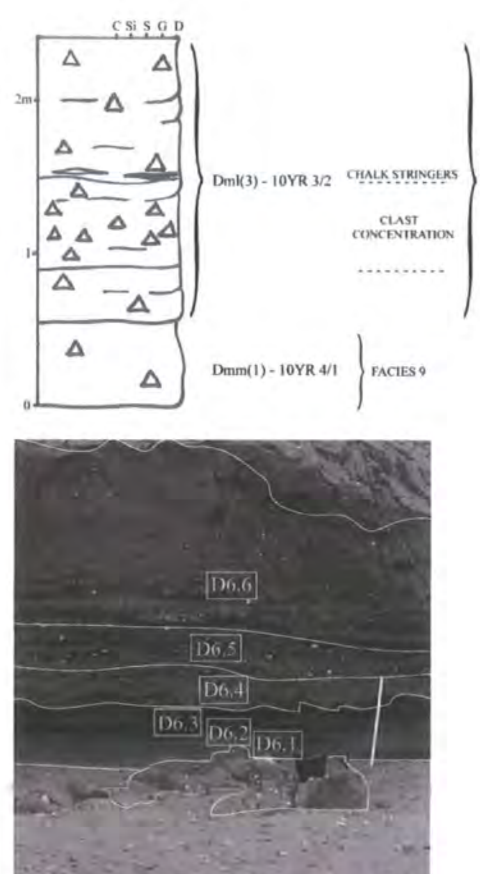
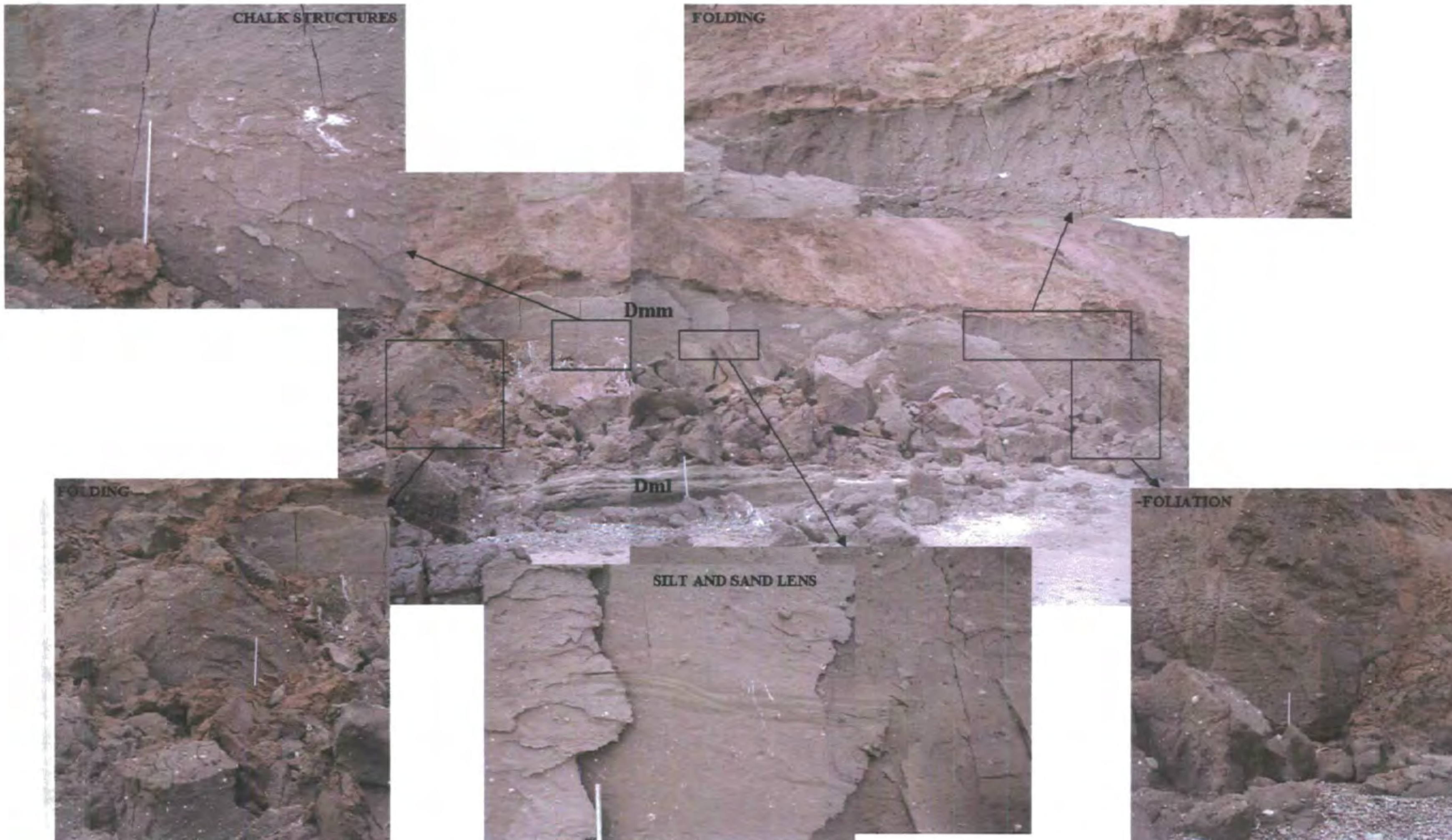


Figure 4.15. Site 6, Dimlington; annotated photograph, section log and sample locations. Metre rule for scale.



.Figure 4.16. Site 7, Dimlington. Metre rule for scale.

Slumping at Site 7 reveals a vertical face of massive diamicton within which lie discontinuous lenses of chalk, sand and silt (Figure 4.16). Laminations within the silt and sand lens are also discontinuous lenses and display evidence of folding and attenuation. Small lenses of chalk within the diamicton also exhibit folding. Further evidence of folding occurs below the massive diamicton at the base of the sequence, where the diamicton is heavily foliated and laminated. Just above beach level thick horizontally-bedded laminations are revealed through the removal of coarser grained laminations through wave action, demonstrating changes in grain size as the cause of the laminations. Further up the sequence, the laminations become finer and display some folding.

Another slump located in the southern section below Dimlington High Land, reveals a complex sequence of diamicton sand and gravel units in the vertical face behind it at Site 8 (Figure 4.16). Unfortunately, the section was too steep and high to enable samples to be taken. A 3.5m thick unit of laminated, clast-rich dark brown diamicton grades into horizontal to low angle laminated clay, where laminations in the diamicton are caused by thin partings of a coarser grain size to the main diamicton matrix. The laminated clay unit progressively coarsens into a dipping laminated sand unit. Between 5 and 5.5m above the beach, a sharp boundary separates a massive diamicton from the sand below. At around 5.8m, a thin light band followed by a band of red diamicton occurs continuously across the section. Immediately above them structures of smeared chalk occur in the diamicton. This diamicton appears slightly lighter and browner than the diamicton below the two bands. A sharp to gradational boundary divides the diamicton from horizontally laminated sands and silts above. Planar cross-bedded gravels rest above these fines, followed by a further unit of horizontally-bedded gravels. The upper boundary of these gravels is undulating, above which lies a thick unit of diamicton. The lowest 0.5m of this unit displays very fine, continuous, horizontal laminations, which grade into a massive clast-poor diamicton.

Site 9 is situated between, and in close proximity to, Sites 8 and 2 (Figures 4.2 & 4.18). The base of the section displays a dark grey-brown laminated diamicton, which contains a lens of gravel at the lowest visible point. Laminations are caused by subtle changes in matrix colour and possible thin (few grains thick) sand partings. The diamicton is replaced by thin bands of white and then black diamicton followed by a thicker band of red diamicton. Although the red band maintains a constant thickness through most of

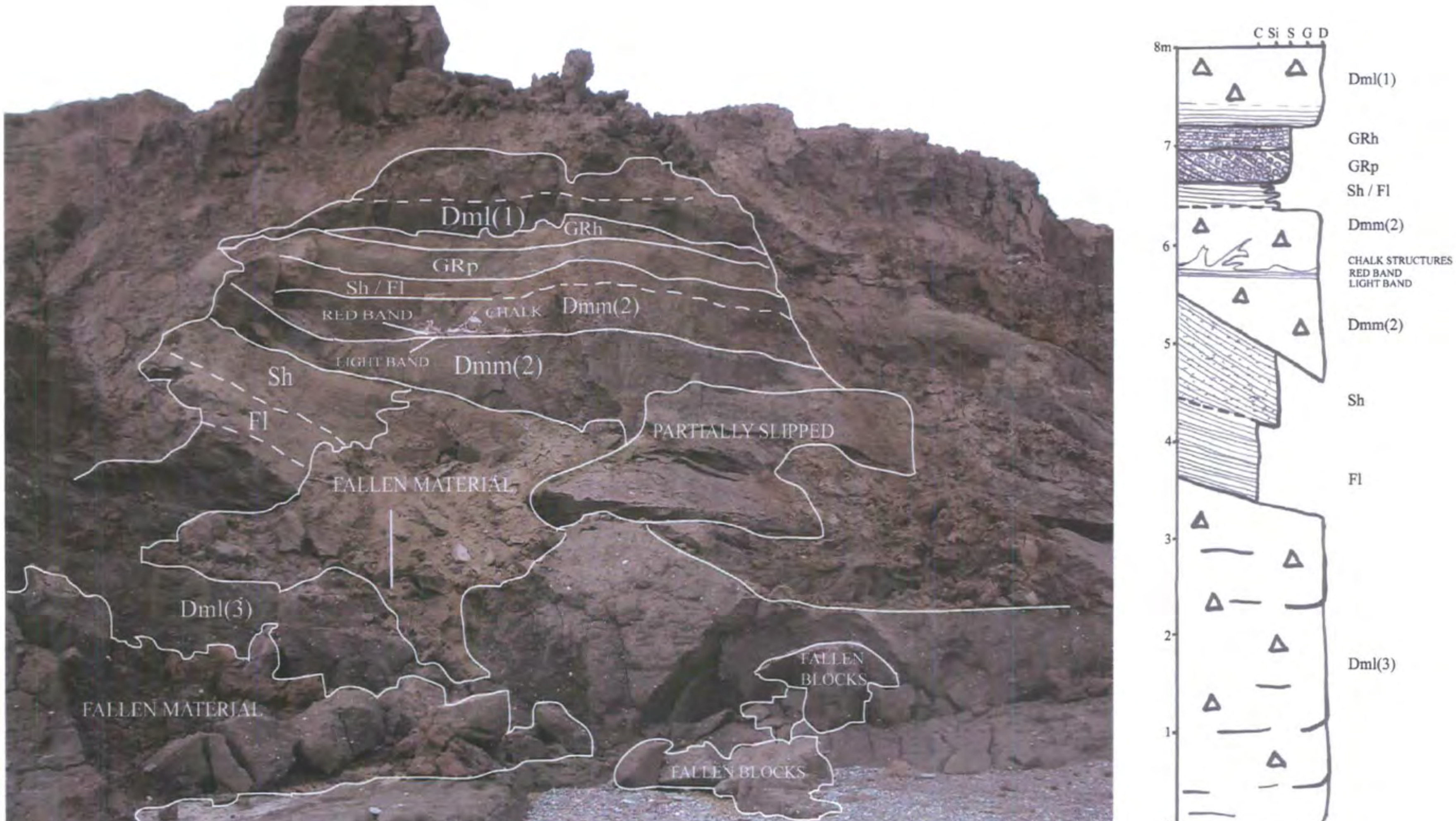
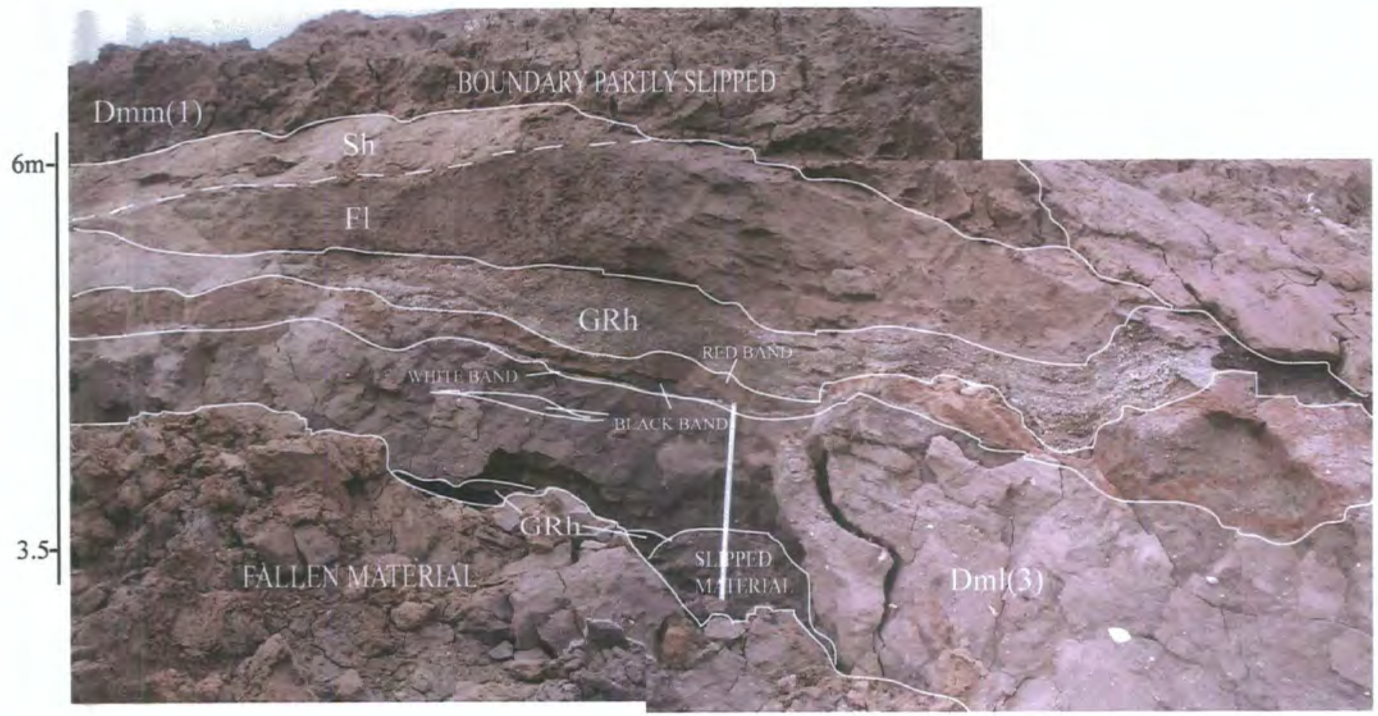


Figure 4.17. Site 8, Dimlington. Metre rule for scale.



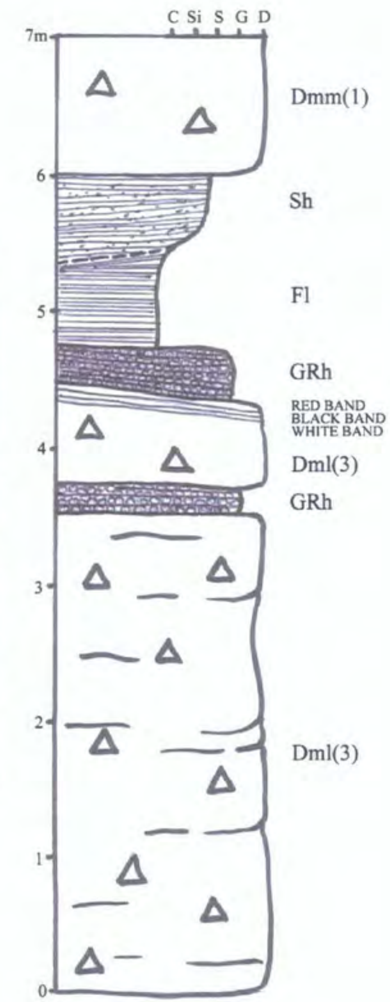


Figure 4.18. Site 9, Dimlington. Metre rule for scale.

the section, it thickens at one end to present an area of mixing with a light grey diamicton. A unit of horizontally bedded gravels, 0.2-0.4m thick, rests above the diamicton bands, above which a unit of horizontally laminated clays grades into horizontally laminated sands. A sharp boundary is observed between the sands and an overlying diamicton unit.

Site 10 is located north of Site 4 below Dimlington High Land (Figure 4.2), where a large slump near the base has exposed a clean section of sand and diamicton about 5m above beach level (Figure 4.19). Despite most of the lower section being heavily obscured and re-worked by the slump, a small outcrop reveals a similar sequence of diamictons to those at Site 2 and 3. The lower diamicton (Facies 2) is clast-rich, dark grey-brown (10YR 4/3 dry), and is diffusely laminated by subtle changes in till matrix colour. A thin (5cm) black and then red band run through the diamicton at a height 2m, above which the diamicton continues but is slightly lighter (10YR 5/3 dry) (Facies 3). Facies 3 reaches a thickness of 1.2m above the black and red bands, before grading into horizontally-bedded, laminated clays (Facies 4). As at Site 2 and 3 no colour change is evident between the diamicton and clay units. Continuous, horizontally-bedded sand laminations begin to appear within the clay around 3.8m from beach level and after a clay thickness of 0.4m, where the unit rapidly grades into the overlying horizontally-bedded sand unit.

Slumping then prevails over the outcrop and the sequence is obscured until just below 6m, where the sharp upper boundary of the sand is shown at the base of the vertical face. It is evident from the slumped material that only sand is present between the two viewable sections. A further unit of massive diamicton (Facies 11), containing mainly shale, sandstone and chalk clasts, rests above the sand and is divided in two by a laterally discontinuous, 0.4m thick, lens of gravels and laminated silts and clays, where the internal structure of the sand and silts contains a series of discontinuous sand and silt lenses. 0.1m below these gravels, a continuous band of red diamicton can be found which pinches and swells along its length. The boundary between this red band and the rest of the diamicton is faint and unclear in many places as it gradually merges into the main diamicton body. Facies 11 is clast-poor and browner (10YR 3/2 moist, 10YR5/3 dry) than Facies 2 and 3, and remains the same directly above the gravel and silt unit. Further up the sequence at 8m above beach level the diamicton and becomes much redder in colour (7.5 YR 5/4 dry). Samples D10.1 to D10.5 were taken from the section

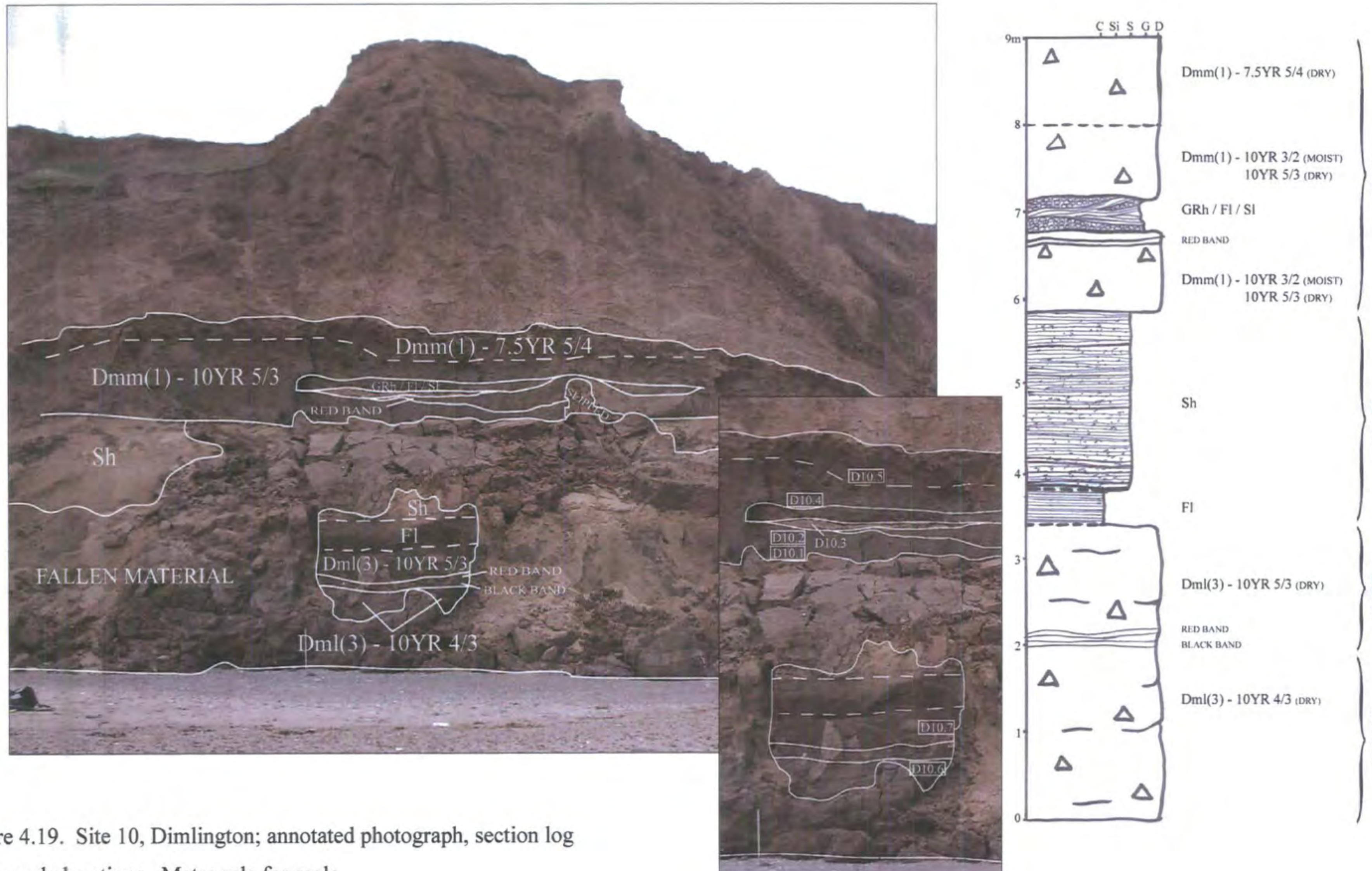


Figure 4.19. Site 10, Dimlington; annotated photograph, section log and sample locations. Metre rule for scale.

above the slumps, where sampleD10.3 was removed from the laminated clays and silts. Samples D10.6 was taken from the dark diamicton 1.5m above the beach, and D10.7, from the lighter diamicton above it (Figure 4.19).

Site 11 is located just north of Dimlington High Land (Figure 4.20). A diffusely laminated dark grey (10YR 5/1 dry) diamicton is observed from beach level to 2.5m in height, where laminations consist of subtle colour changes and possible thin sand partings. This is separated from a dark brown (10YR 5/2 dry) clast-rich diamicton by a unit of laminated (caused by changes in grain size) fine sediments, which varies in thickness from 0.5 – 1.5m, which are the same colour as the diamicton below. The upper diamicton is predominantly massive, but contains areas of fine foliation, detected by changes in surface morphology due to changes in grain size.

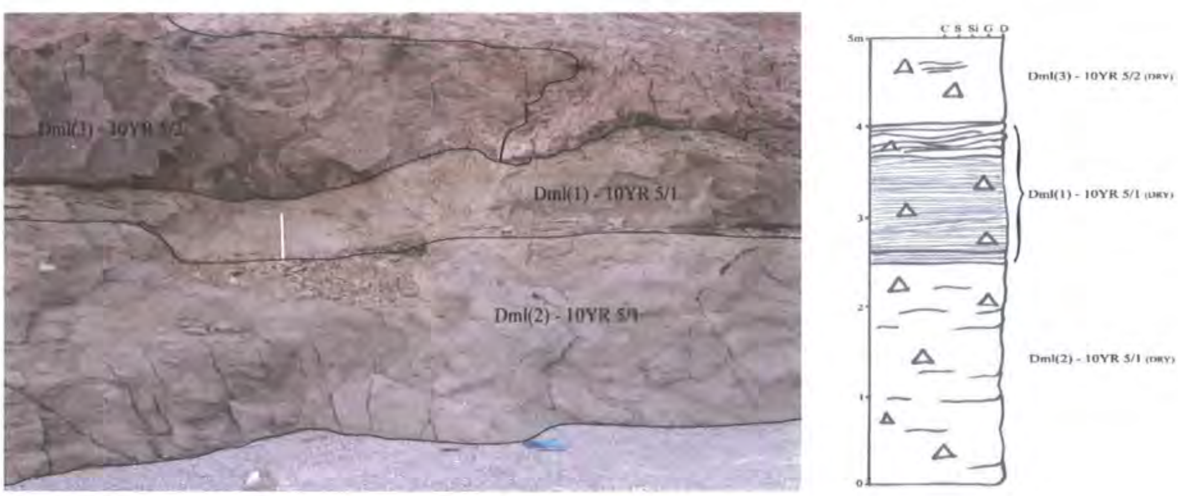


Figure 4.20. Site 11, Dimlington. Metre rule for scale.

Facies Association Summary

Facies 1 (DF1) (Sites 2, 3) - Diamicton in this group is massive and chalk-rich, although chalk content increases upwards. The matrix is predominantly dark brown in colour, but varies between 10YR 4/1, 10YR 3/2 and 10YR 4/2.

Facies 2 (DF2) (Sites 2, 3, 4, 8, 9, 10) – Consists of diffusely laminated diamicton, comprising of a number of bands of diamicton differentiated by slight differences in colour. Facies 2 contains less clasts than Facies 1 and is also generally slightly lighter in colour (10YR 4/2 or 10YR 3/2). Clasts are predominantly shale and sandstone rather than chalk.

Facies 3 (DF3) (Sites 2, 3, 4, 8, 9, 10) – Includes massive diamicton, which is predominantly very light in colour (10YR 4/2 and 10YR 5/2) and rich in chalk clasts. However, the unit often displays significant amounts of incorporation and mixing with other diamicton. This diamicton is often very red (7.5YR 3/2 and 5YR 4/4) and contains a different suite of clasts i.e. principally shale and sandstone. At a number of sections, there is a thin discontinuous grey-black (Gley N/4) diamicton band, 2-3cm thick, followed by a thin discontinuous band of red diamicton, which divides Facies 3 from the underlying Facies 2. Gravel and granule pendant structures are also found within this unit.

Facies 4 (DF4) (Sites 2, 3, 4, 8, 9, 10) – Consists of stratified sediments where horizontally bedded clay grades into horizontally bedded sand. No ripple structures or cross-laminations occur in these sediments. In most places the underlying diamicton in Facies 3 grades into the clay layers of Facies 4.

Facies 5 (DF5) (Site 5) – Describes dark, grey-brown, diffusely laminated diamicton, where laminations are the result of subtle changes in colour. There is a sharp change in colour upwards from 10YR 3/2 to 10YR 4/2, but this is believed to correspond to a high tide water mark and therefore is likely to represent a change in moisture content within the diamicton. The diamicton contains a moderate to abundant amount of clasts.

Facies 6 (DF6) (Site 5) - A sharp boundary divides Facies 6 from Facies 5. Laminations in Facies 6 are also caused by subtle colour changes, but the general matrix colour is much browner than Facies 5 (10YR 4/3). There is a notable change in clast content across the boundary from clast-rich to clast-poor. However, the diamicton soon becomes clast-rich again and Facies 6 is therefore predominantly clast-rich.

Facies 7 (DF7) (Site 7) - Facies 7 is separated from Facies 6 by a laterally continuous sand-supported gravel unit. Facies 7 is the same colour as Facies 6 (10YR 4/3) and possesses a similar sedimentary architecture (diffuse laminations due to changes in colour). The similarity of Facies 6 and 7 infers that it is possible that they both correspond to the same diamicton unit. However, since the origin of the gravel unit dividing the two is unclear at this point, it seems sensible to retain this division.

Facies 7 extends upwards for about 10m and includes distinct bands of different coloured diamicton, which contain varying amounts of chalk clasts, towards the top of the unit. Above these bands, the laminations within the diamicton become less distinct and grade into massive diamicton, which then becomes increasingly weathered (Facies 8). The exact boundary between Facies 7 and 8 is indefinable.

Facies 8 (DF8) (Sites 1, 5) - Consists of weathered, massive diamicton at the top of the Dimlington sequence, which progressively changes in colour from 10YR 4/3 to 7.5YR 4/3 or 7.5YR 4/2 and becomes much more heterogeneous. The diamicton remains clast-rich, but chalk clasts become increasingly rare, with the predominant clasts being shale, sandstone and limestone.

Facies 9 (DF9) (Site 6) - This diamicton is dark grey (10YR 4/1), massive and clast-poor. It is separated from Facies 10 by a distinct boundary.

Facies 10 (DF10) (Site 6) - Facies 10 is a brown (10YR 3/2) diamicton containing laterally discontinuous laminations of coarser grained sediments, which are defined by differential weathering. It is clast-rich and contains much more chalk and limestone clasts than Facies 9. In colour, clast content and sediment architecture it may be comparable to Facies 2.

Facies 11 (DF11) (Site 10) – Consists of massive diamicton, which contains predominantly shale, sandstone and chalk clasts. Discontinuous bodies of gravels, laminated silts and clays occur towards the base of this unit. The Munsell colour of the matrix is 10YR 3/2, comparable with Facies 2. However, the unit grades into a much redder diamicton (7.5YR 5/4) higher up.

4.2.2 Skipsea (TA 182552 – 179559)

Skipsea village is located north of the outcrop of Withernsea Till on Holderness (Figure 1.4), and only Skipsea Till is exposed along the cliffs here. Madgett & Catt (1978) designated this location the type site for the Skipsea Till after the cliff exposures found. Four sites were studied at Skipsea on accessible cliff sections to the north of the Skipsea road, and their positions are shown in Figure 4.21. At Sites 1 and 3, it was possible to combine a number of small sections at varying heights to create composite sections of

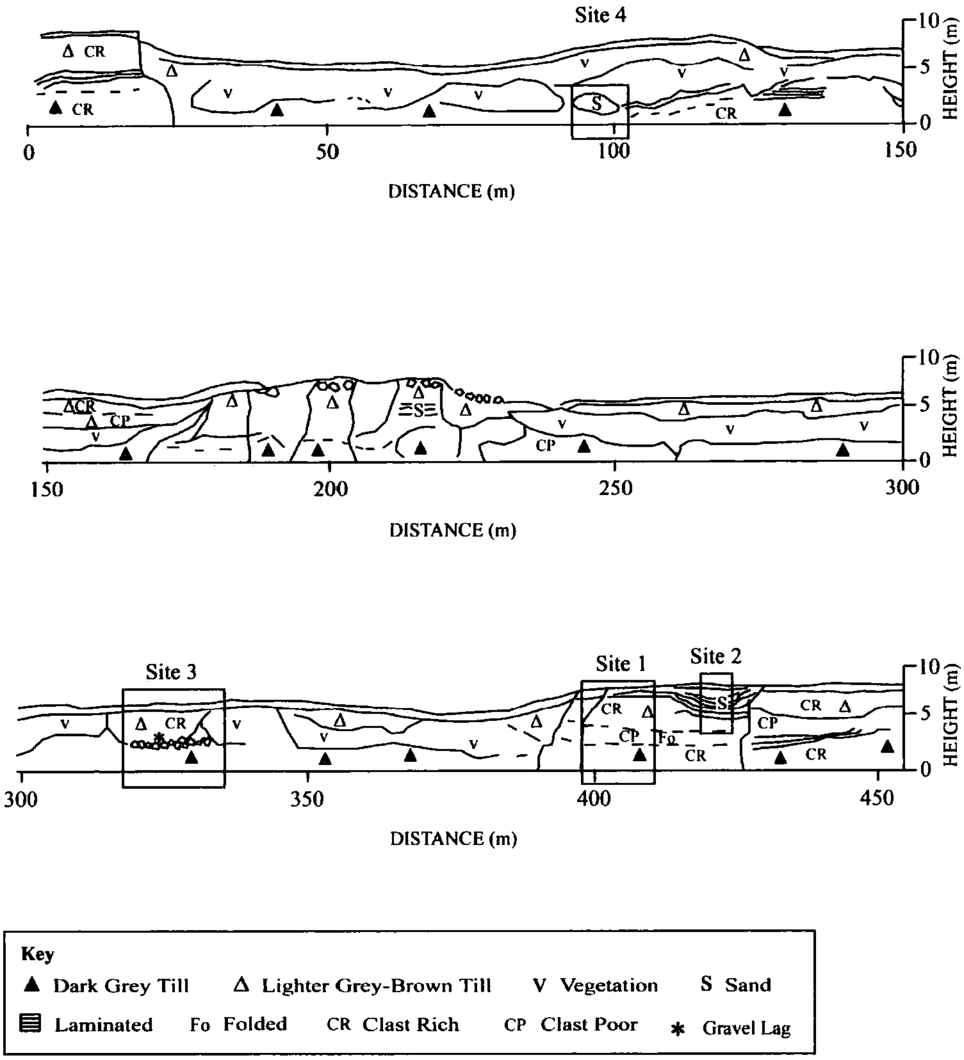


Figure 4.21. Site log, Skipsea, including study site locations. Compiled in Nov 2006.

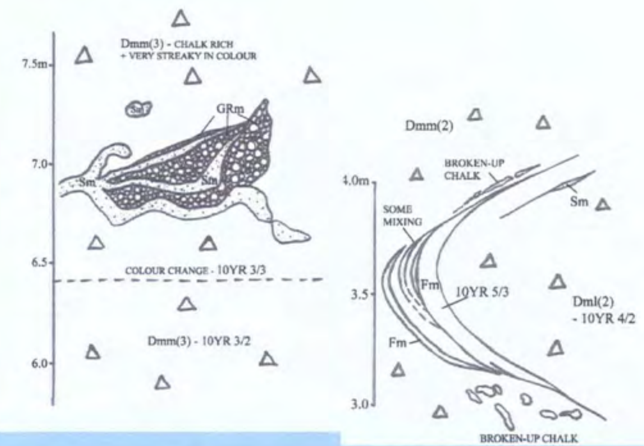
the whole vertical cliff height. This was done using Sites 1A, 1B and 1C at Site 1 (Figure 4.23), and Sites 3A, 3B, and 3C at Site 3 (Figure 4.27). At Site 3 samples were taken from an additional section, Site 3D, in order to gain repeat samples from above and below a band of gravels. Site 3D is therefore equivalent to the upper portion of Site 3A and to Site 3B and so is not included in the composite log for Site 3. Site 2 consists of Site 2A and Site 2B which record a sand and clay sequence towards the top of the diamicton cliff (Figure 4.24). Site 2B is located next to Site 2A, and therefore logs for this site are based on Site 2A. Site 4 is located at the base the cliffs and records a sand and diamicton sequence within the diamicton cliffs (Figures 4.28 & 4.29).

Site 1 consists of an 8m high sequence of laminated and massive matrix-supported diamictons (Figures 4.22 & 4.23). The lowest unit (Facies 1) is a dark grey-brown (10YR 4/2) clast-rich, diffusely laminated diamicton. Laterally continuous laminations occur intermittently within this unit, where thin beds of sand and silt, perhaps only a few grains thick, can be identified through differential weathering. Clasts within this diamicton are predominantly shale, mudstone and sandstone. A horizontal hollowed out band 2.8-3.0m above beach level indicates the presence of a discontinuous lens of coarser material, and separates this unit from another laminated diamicton above.

This diamicton is again diffusely laminated, but laminations are around 0.1m thick and are denoted by a combination of subtle changes in colour and some thin sand lamina. The unit is the same colour as the lower diamicton, and although it contains a similar clast assemblage to the lower diamicton, the concentration of clasts is less. At the northern side of the section, the lens of coarser material disappears, and weathering on the outer layer of the diamicton becomes more pronounced, making the abundance of clasts the only distinguishing feature between the two units. A recumbent fold of clay is also found in this diamicton. The clay is light brown (10YR 5/3) and smeared chalk clasts appear on either side of it. A 'tail' of smeared chalk from the clay is folded again below the clay fold and pinches out into the lower diamicton. A large lens of disintegrated chalk is also found below the fold.

The laminated diamicton progressively grades into massive diamicton (Facies 2) at about 4.5m above the beach. The unit is a lighter brown than the lower two (10YR 3/2) and although it contains a similar concentration of clasts to the unit below, there is a significant increase in limestone and chalk clasts in this unit. The diamicton is a maximum of 2m thick and grades into a 1m thick weathered unit at the top of the sequence. The lower portion of weathered diamicton is light brown (10YR 3/3), but becomes heterogeneous in colour, displaying streaks of orange, purple and green. Discontinuous lenses and pods of sand and gravel occur in the middle of this section.

Site 2 focuses on a sand and gravel unit deposited in a hollow on the surface of the diamicton about 10m north of Site 1 (Figures 4.24 & 4.25). The diamicton (Facies 2) is clast-rich, dark grey-brown. Clasts within this diamicton are predominantly limestone, although some large sandstone clasts are present. Other smaller clasts include chalk, shale, flint and porphyry. The diamicton reaches a height of 5.1m before horizontally-bedded to massive sand, 0.1m thick, rests on its undulating surface. Above the sand, a 1m thick unit containing centimetre-thick beds of sand and clay has been heavily faulted



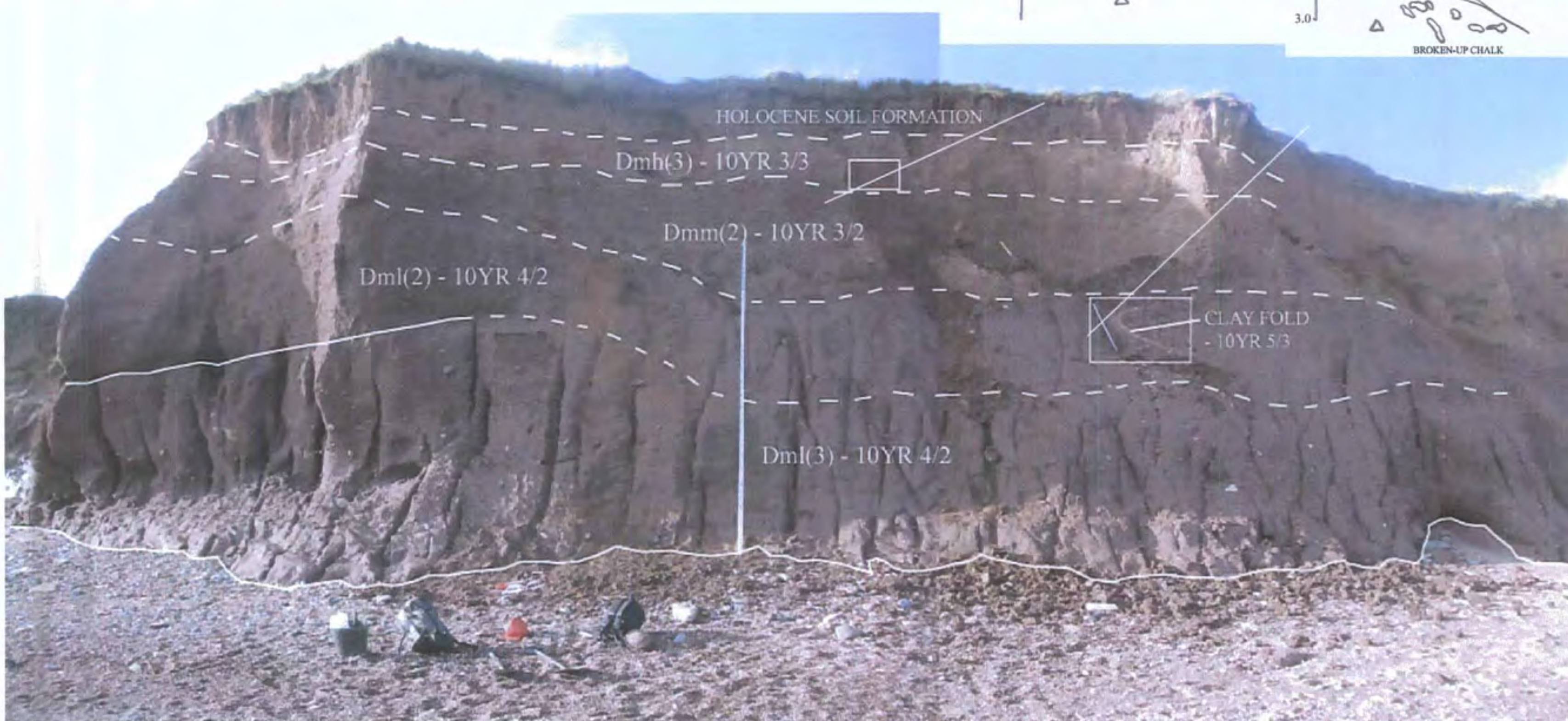


Figure 4.22. Site 1, Skipsea; annotated photograph and section logs. Metre rule by clay fold for scale.

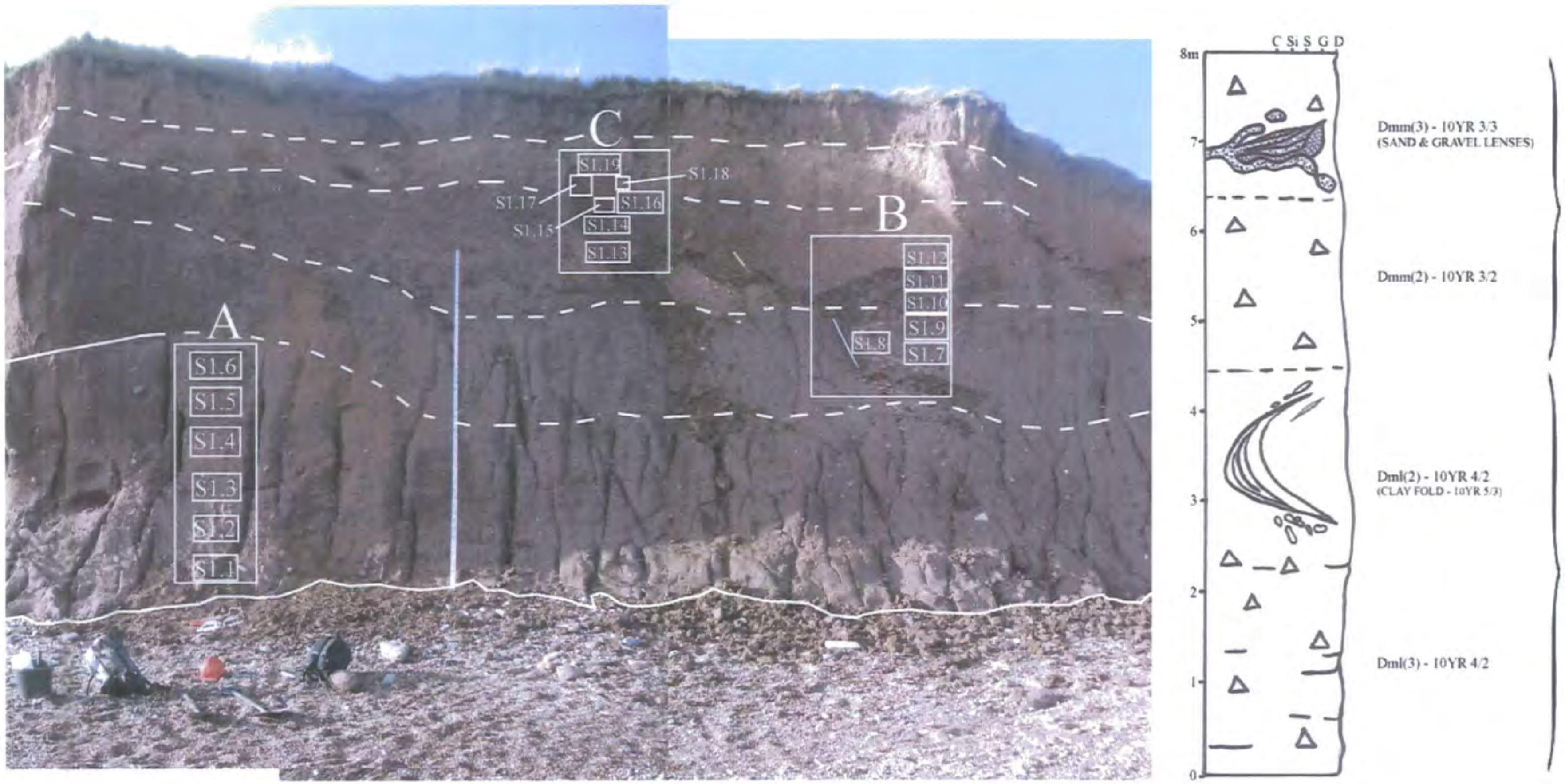


Figure 4.23. Site 1, Skipsea; section log and sample locations, illustrating Sites 1A, 1B and 1C. Metre rule by clay fold for scale.

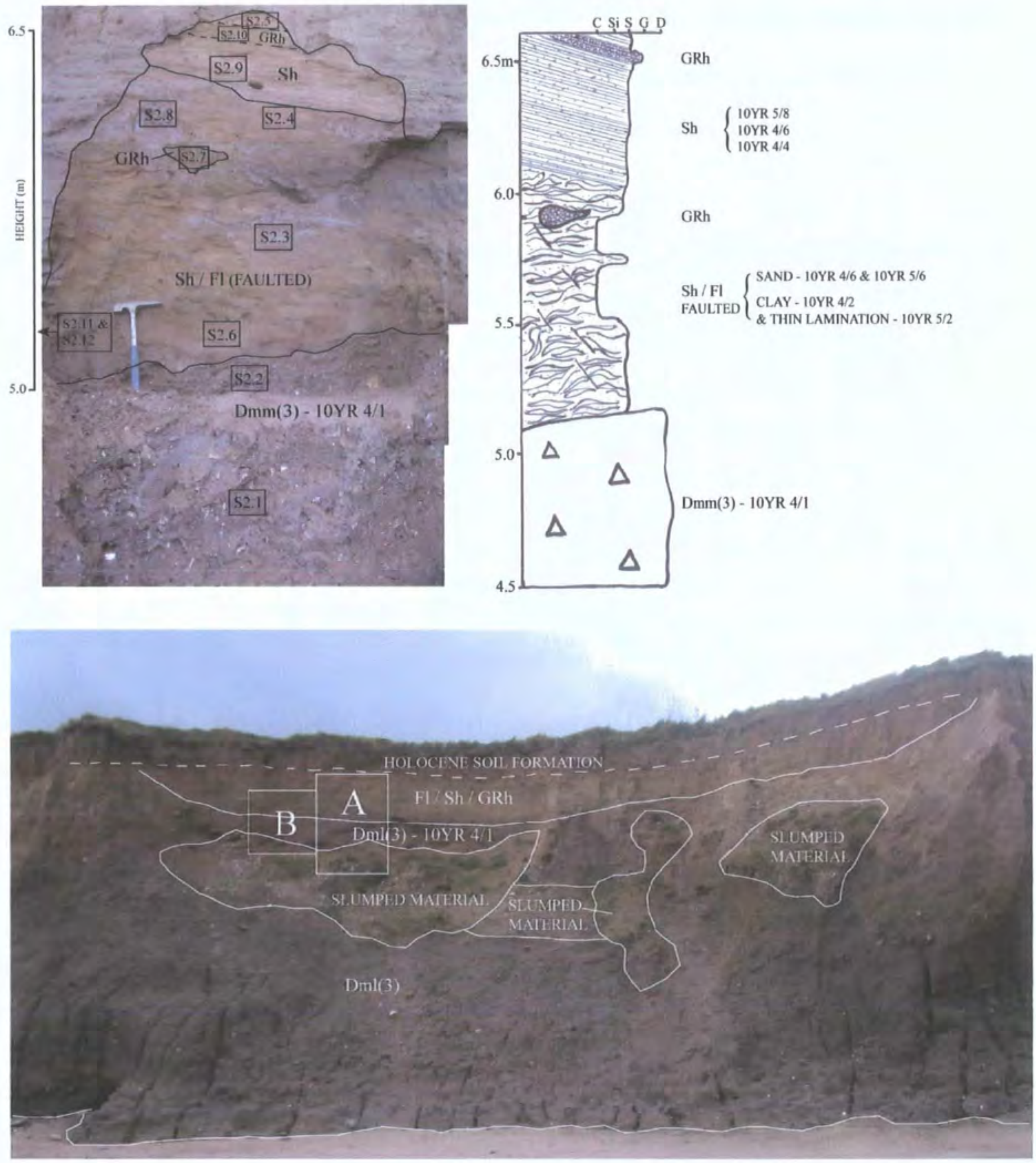


Figure 4.24. Site 2, Skipsea; section logs and sample locations. Geological hammer for scale.

and contorted, where the primarily orange (10YR 4/6) sand contains lighter sand intraclasts (10YR 5/6). Clay is more abundant in the upper half of this unit. It is predominantly dark grey-brown (10YR 4/2) in colour, comparable to the diamicton below, although it contains sporadic thin, light grey (10YR 5/2) clay lamina only a few millimetres thick. No large clasts are found, but small granules (< 8mm) are found scattered within the unit, mainly within the sand. A pod of granules and gravels is found towards the top of this unit and contains a similar clast assemblage to the

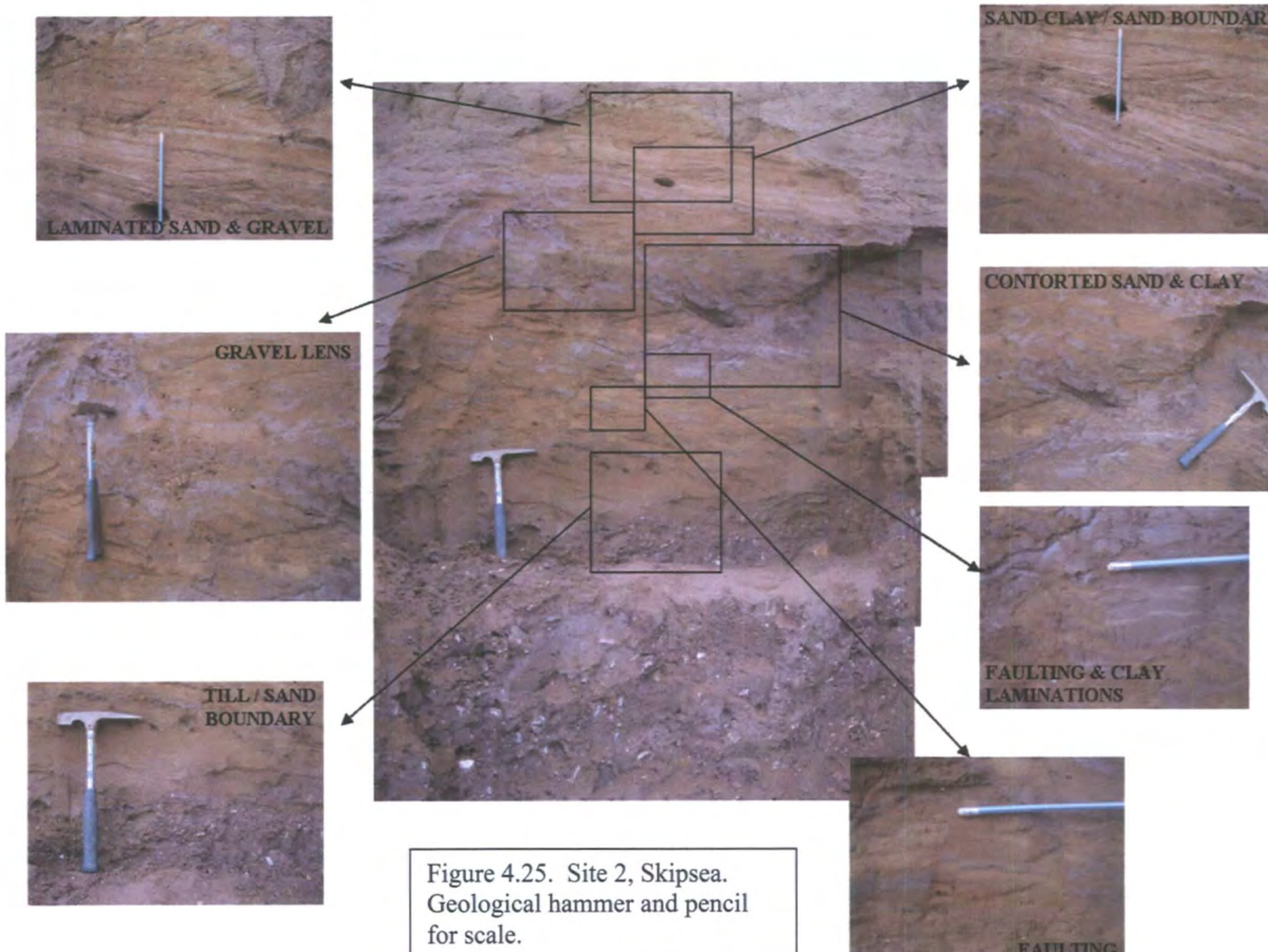


Figure 4.25. Site 2, Skipsea. Geological hammer and pencil for scale.

Figure 4.26. Site 3, Skipsea; annotated photograph. Metre rule for scale.

diamicton below. A sharp boundary separates this unit from an upper unit of low angle cross-laminated sands (10YR 4/4, 10YR 4/6, 10YR 5/8), dipping at 15° to the north. An 8cm thick bed of granules, containing predominantly sandstone, quartz and flint, lies within the sands after 0.4m, after which the grain size fines again.

Site 3 displays a laminated diamicton (Facies 1) separated from a massive diamicton (Facies 3) by a matrix-supported concentration of clasts, which cover a spectrum of sizes from over 200mm downwards (Figures 4.26 & 4.27). The lower laminated unit is dark grey-brown (10YR 3/2), clast-rich, and contains intermittent laterally continuous sand partings observable through the weathering out of these laminae. Towards the base, at a height of 0.8m, a light brown (10YR 4/3) discontinuous clay band occurs which is observable for a length of about 1.5m. The band swells to a maximum of 7cm and pinches in the middle and at the ends. A sandy-clay lamina, less than a centimetre thick, can be picked out by the change in texture and colour at 1.7 to 1.8m above the beach. The whole diamicton unit is very similar to the lowest unit at Site 1 in terms of clast lithology and density, colour and lamination style, although laminae appear slightly denser at Site 3. The height of the band of clasts varies from 2 to 3.1m from south to north across the section. The assemblage of clasts within the clast lag or boulder pavement is very similar to those in the diamicton below it. The remainder of the section above the band of clasts is denoted by a massive dark brown diamicton (10YR 4/2 – 10YR 4/1). Facies 3 is equally clast rich compared to the Facies 1, but the clasts are predominantly limestone, although small chalk clasts are plentiful. At the base of this unit a laterally continuous fine sandy lamination about 1.5cm thick (colour 10YR 4/3) is draped over the clast band. Another very thin continuous sandy lamination is found about 0.5m up in the unit. In the upper 1m of this 2.8m unit, the diamicton becomes increasingly weathered. Clasts become sparser and the diamicton becomes streaked in colour with purple and orange.

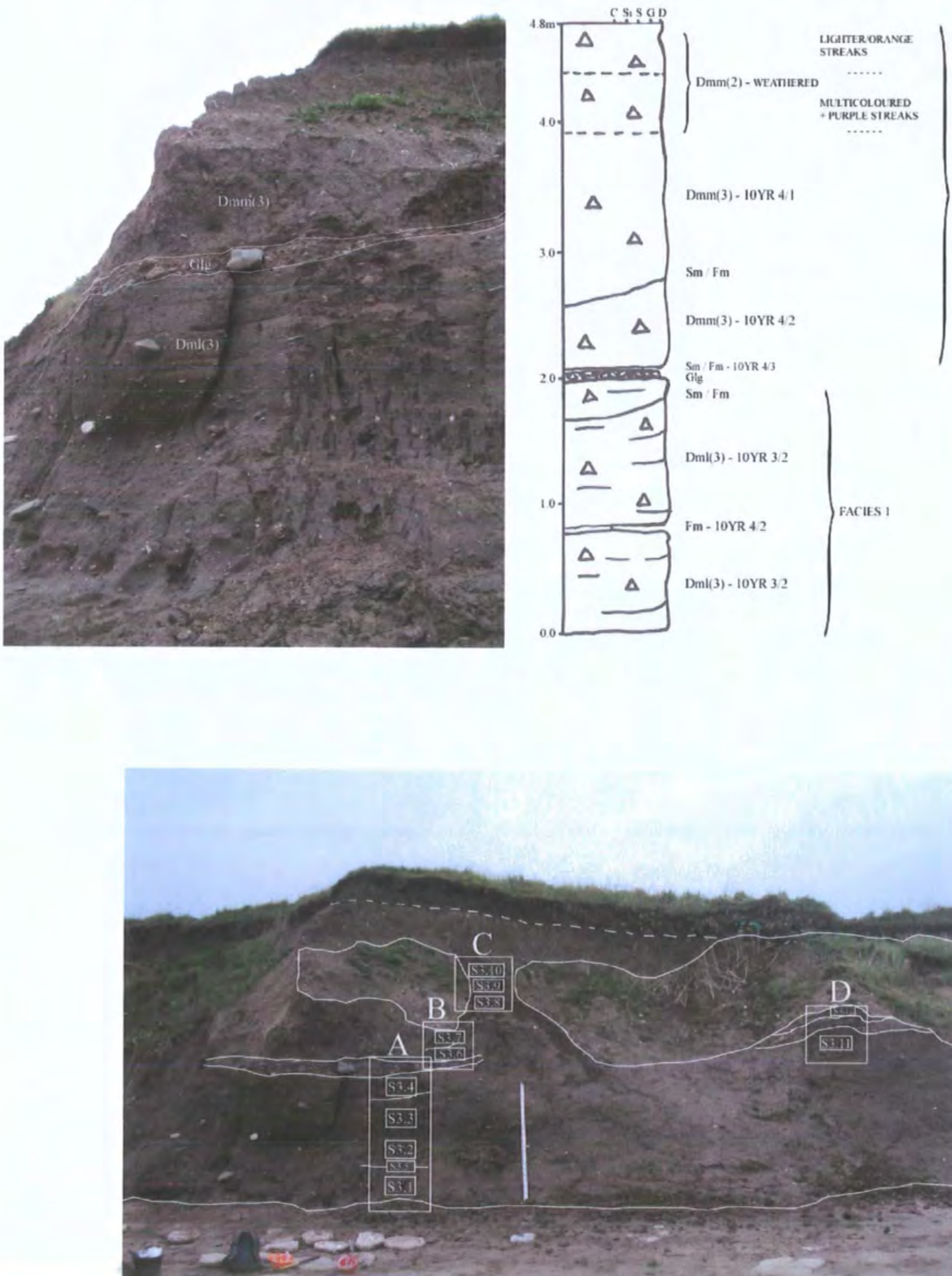


Figure 4.27. Site 3, Skipsea; section logs and sample locations. Metre rule for scale.

At Site 4, a 0.3-0.5m thick unit (Facies 4) of centimetre thick sand and clay laminations occurs about 1.5 to 2.5m above the beach (Figure 4.29). The laminations can be traced for at least 10m northwards before slumping obscures any further observations. In places the sand and clay layers appear as horizontally-bedded lamina, whilst in other areas the sand appears as small pod or lenses, pinched at either end within the clay. Other places show evidence of faulting and folding, which confuse the sequence of deposition. Southwards, the laminations open out to reveal a large unit of laminated sand, 1.3m high at its maximum and at least 3 metres in length, interrupted by a number of bands of diamicton (Figure 4.28). The majority of the base of the sand cavity at Site 4 is unobservable, but a small visible area to the north of the section, reveals 0.2-0.3m of clast-rich dark grey-brown (10YR 3/2) laminated diamicton (Facies 1), which is rich in chalk casts. Laminations are caused by subtle changes in colour and thin sand partings. This lower diamicton rapidly rises upwards to the north, as the cavity pinches out into the unit of sand and clay laminations. The upper contact at the northern end of the cavity is also obscured by slumping, but the part that is visible shows the contact gently sloping towards the southern end of the section.

The main hollow of sand consists of horizontal to low angle cross-bedded, fine laminations that have been asymmetrically folded and varyingly attenuated. Deformation structures are more intense in a large area of sand at the southern end, where the bedding is almost convolute. At the northern end the sand is dissected by a number of bands of diamicton which are steeply angled. They stem from a single band at the base of the unit and increasingly divide northwards and upwards. Clast content within the bands is low, where the predominantly shale or sandstone clasts are scarce and generally smaller than in the main diamicton units above and below. The sand laminations appear draped over these diamicton bands, and there is less evidence of folding of the sand in the areas between them. The lower boundary between the diamicton and sand is sharp, but the upper contact is both sheared and loaded. Fine clay laminations from the diamicton run through the top of the sand unit towards the southern end and pendant structures of diamicton and clay occur from the diamicton into the sand. Discontinuous laminations of sand also occur in the basal layers of the diamicton. The upper diamicton (Facies 5) is massive and very similar in colour (10YR 3/2) and clast content to the lower diamicton, where clasts are predominantly shale, sandstone and limestone, with smaller clasts of chalk and red marl.

Figure 4.28. Site 4, Skipsea; annotated photograph and sketch. Metre rule for scale.

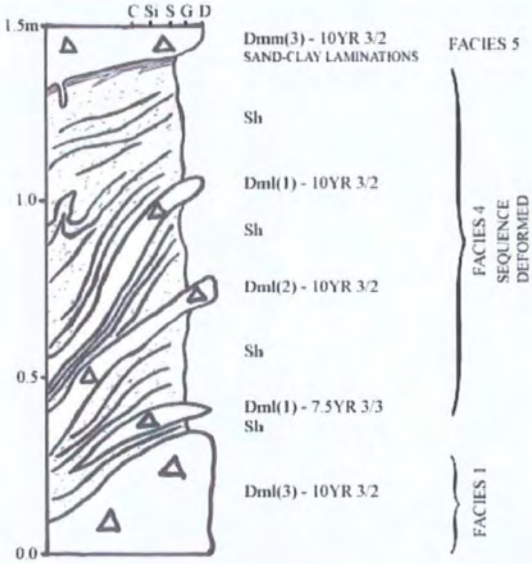
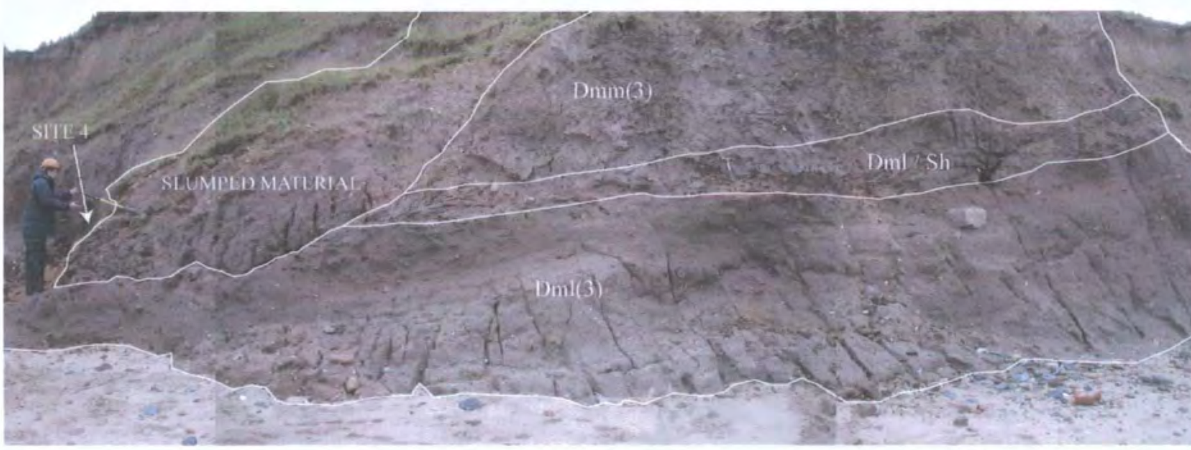
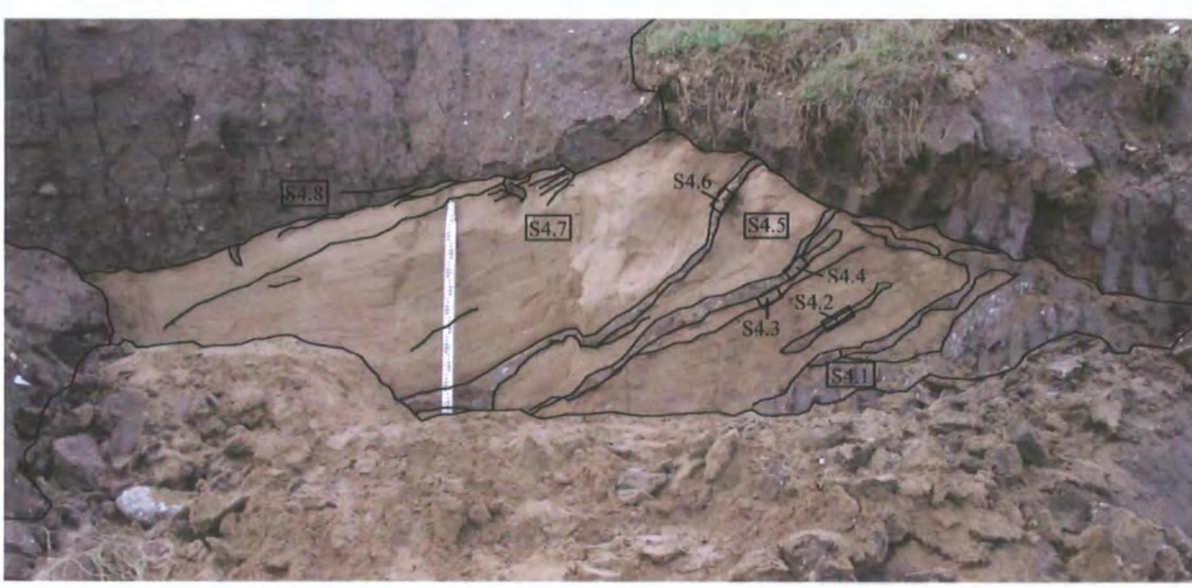


Figure 4.29. Site 4, Skipsea. Top to bottom: Section log; Site 4 overview; sample locations. Metre rule for scale.





Facies Association Summary

Facies 1 (SF1) (Sites 1, 3, 4) – Consists of a dark, grey-brown (10YR 4/2), clast-rich, diffusely laminated diamicton. Laminations are laterally continuous and occur intermittently as thin beds of sand and silt, which are identified by differential weathering. Higher up in the unit, laminations appear to be caused more by subtle changes in matrix colour as well as sand lamina. Clasts within this facies are predominantly shale, mudstone and sandstone.

Facies 2 (SF2) (Sites 1 and 2) – Facies 1 grades into Facies 2, which comprises of a massive, clast-rich diamicton. The unit is a lighter brown (10YR 3/2) than Facies 1 and contains a significantly higher proportion of chalk and limestone clasts. The upper section of this facies possesses some weathering.

Facies 3 (SF3) (Site 3) – Facies 3 is a massive, clast-rich, dark brown (10YR 4/2 – 10YR 4/1) diamicton. Clasts are predominantly limestone and chalk. Occasional thin sand laminations occur within the unit. The upper section of this facies possesses some weathering. The facies is comparable with Facies 2, however, it is separated from Facies 1 by a clast lag or pavement, compared to at Site 1 where Facies 1 grades into Facies 2. Therefore this unit is assigned an individual facies number.

Facies 4 (SF4) (Site 4) - Consists of a sand and clay unit. In some places sand and clay layers appear as horizontally-bedded lamina, whilst in other areas they appear as small pods or lenses. A number of areas also display evidence of folding and faulting.

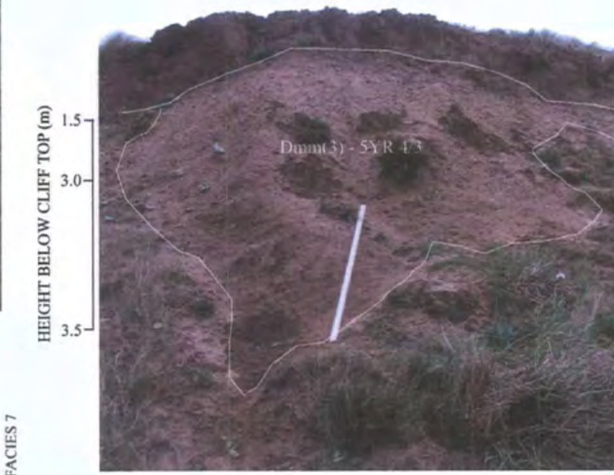
Facies 5 (SF5) (Site 4) - Includes a massive diamicton which is similar in colour (10YR 3/2) and clast content to Facies 1. Clasts are predominantly shale, sandstone and limestone.

4.2.3 Filey Brigg (TA 125816)

Filey Brigg is a peninsula of Corallian Limestone, situated at the northern end of Filey Bay. 30 – 40m of diamicton, previously recognised as late Devensian glacial till (Edwards, 1981; Evans *et al.*, 1995) rests upon the limestone outcrop, providing the highest vertical succession of sediments in this research. Three sites were examined at Filey Brigg, where Sites 1 and 2 combine to create a composite log spanning the total 35m height of the cliff (Figure 4.30). Site 3 is located 30m south of Sites 1 and 2, where the diamicton cliffs extend directly upwards from beach level and no bedrock is visible (Figures 4.32 & 4.33). Clasts within the diamicton at all three sites are predominantly composed of shale, sandstone and limestone. Quartz, porphyry (Cheviot), flint, coal and siltstone were also found within some samples.

At Site 1, 3m of Corallian Limestone bedrock is covered by up to 9.8m of dark brown (10YR 4/3) predominantly massive diamicton (Facies 4). Sand laminations occur intermittently within this diamicton, especially towards the top of the unit. Above this facies, a 2m thick laminated diamicton unit occurs (Facies 5). Here, thin (< 1cm) continuous laminations, primarily sand, but with some clay are much denser than lower in the section. There is no internal structure within the sand laminations. The influence of sand in this unit lightens the colour slightly to 10YR 4/4. Beds of horizontally bedded coarse and fine gravel, sand and clay rest on the laminated diamicton below. Discontinuous lenses of gravels and clay occur sporadically within these beds. These beds comprise a total thickness of 1.6m before the succession returns to massive diamicton (7.5 YR 3/3) (Facies 6). Within Facies 6 the diamicton is again occasionally interrupted by isolated sand laminations. At a height of just over 20m, a unit of sandy-clay diamicton occurs. The exact thickness of this unit is undeterminable due to the transitional nature of the boundary, but it is roughly 0.5m. Slumping made the upper portion of the section unexaminable and so it is unclear whether further sandy units occur higher up. A small section at the top of the cliff is recorded as Site 2. Here 4m of orange- brown (5YR 4/3) massive diamicton is exposed (Facies 7). The diamicton appears sandier and is clearly weathered. Twenty-four samples were taken along a vertical transect at Site 1, and four samples were taken at Site 2 (Figure 4.31).

At Site 3 (Figures 4.32 & 4.33), the succession is heavily laminated and folded, and differential weathering of the coarser material has defined these structures. All the units in this sequence are clast rich. The lowest unit (Facies 1) consists of a dark grey-brown (10YR 4/2) diamicton, less than 0.8m thickness from beach level. Laminations in this unit are laterally discontinuous and appear finer and less densely spaced compared to the overlying diamicton. Facies 2 rests on the undulating surface of the Facies 1 and



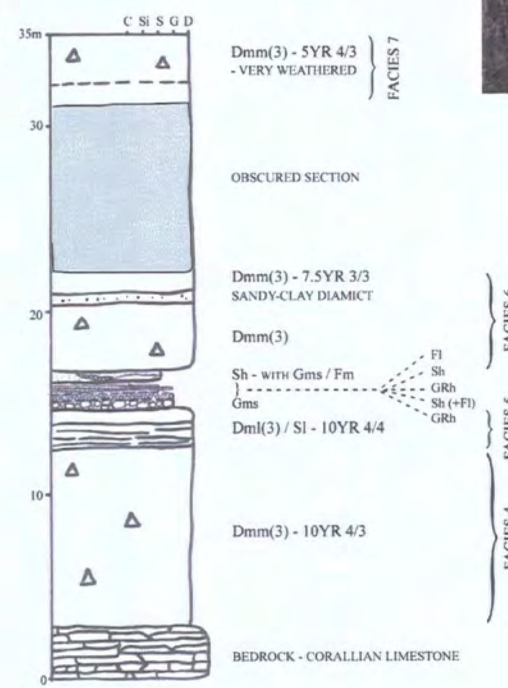


Figure 4.30. Sites 1 and 2, Filey; annotated photographs and log. Clockwise from top left: Site 1; Site 2; Sites 1 and 2 section log; sands and gravels, Site 1 Filey. Metre rule and geological hammer for scale.

Figure 4.31. Filey Sites 1 and 2; sample locations. Clockwise from top left: Site 1A, Site 2, Site 1B.

has a maximum thickness of 0.4m. It is lighter and redder that Facies 1 (10YR 4/3) and contains slightly coarser, laterally discontinuous laminations. Its upper surface mirrors its lower undulated surface, although in places it appears more subdued. Above this facies a much thicker (~ 2m) unit (Facies 3) occurs of light brown (10YR 5/3) laminated diamicton. Facies 3 is very heavily laminated and folded, and contains a large chevron fold. The pronounced definition of these structures through weathering indicates that the laterally discontinuous laminations are caused by changes to a coarser grain size. A discontinuous gravel bed towards the top of the unit fills the large troughs between the chevron fold. The laminated diamicton grades into an overlying unit of massive diamicton, which extends towards the top of the cliff. No colour change is apparent between the laminated and massive units. The sequence is capped by a reddish-brown diamicton. Two samples were taken from the lower diamicton, one from the middle, and two from the upper diamicton (Figure 4.33).

Figure 4.32. Site 3, Filey; annotated photograph.

Facies Association Summary

Facies 1 (FF1) (Site 3) – Comprises a dark, grey-brown (10YR 4/2), clast-rich laminated diamicton. Laminations are laterally discontinuous and consist of thin sand partings which are less densely spaced than within the overlying Facies 2.

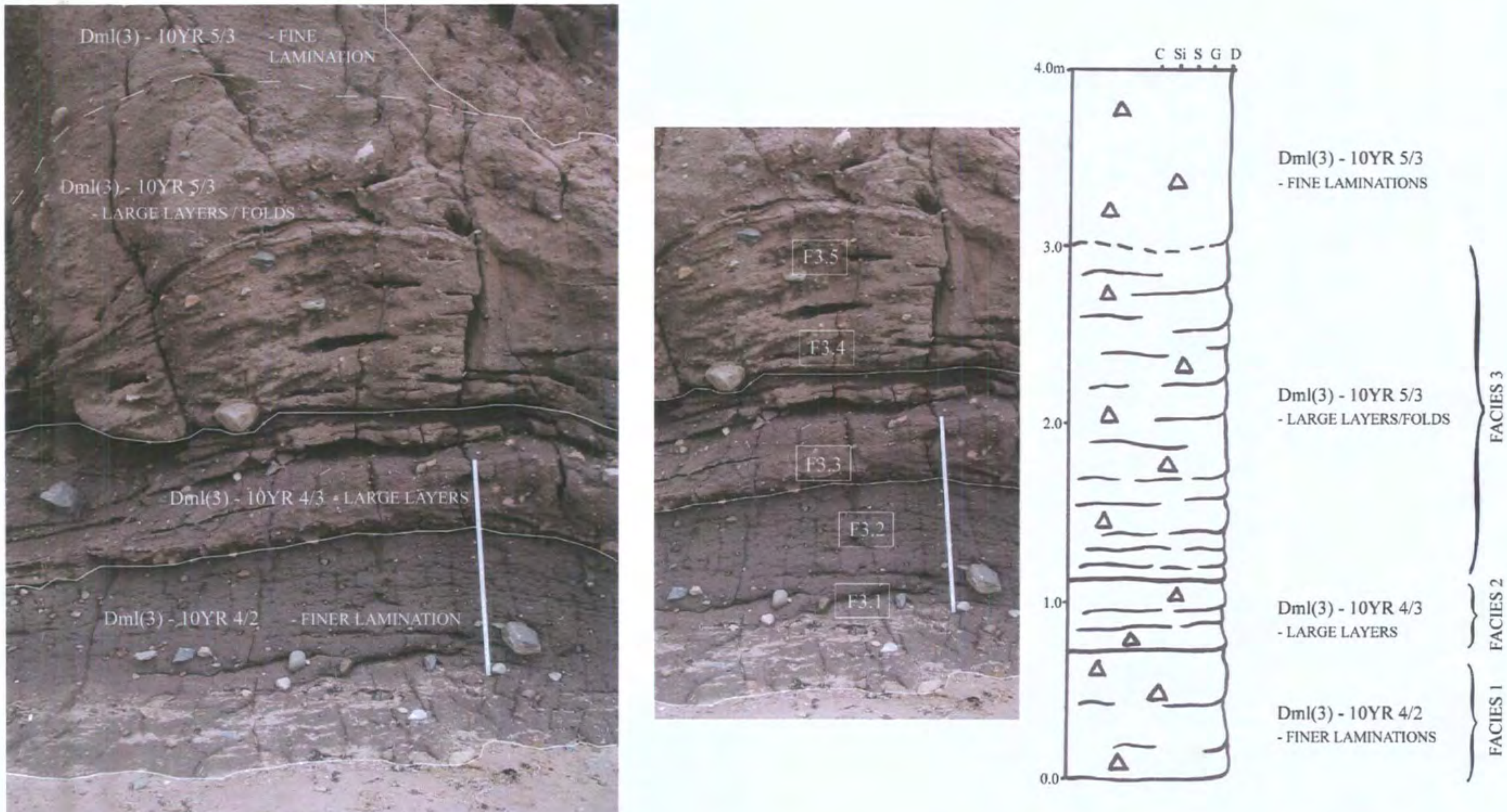


Figure 4.33. Site 3, Filey; section logs and sample locations. Metre rule for scale.

Facies 2 (FF2) (Site 3) – Consists of a lighter, redder (10YR 4/3), clast-rich diamicton than Facies 1, which contains slightly coarser, laterally discontinuous laminations.

Facies 3 (FF3) (Site 3) – Consists of a light brown (10YR 5/3), clast-rich, discontinuously laminated diamicton. Laminations are dense and heavily pronounced by differential weathering, indicating thicker laminations of coarse sediment. The laminations highlight undulating folds within the diamicton as well as a chevron fold in one place. Areas of gravel are also found within the diamicton particularly around the chevron fold.

Facies 4 (FF4) (Site 1) – Facies 4 is a predominantly massive, dark brown (10YR 4/3), clast-rich diamicton. Thin, laterally continuous sand laminations occur intermittently within this unit.

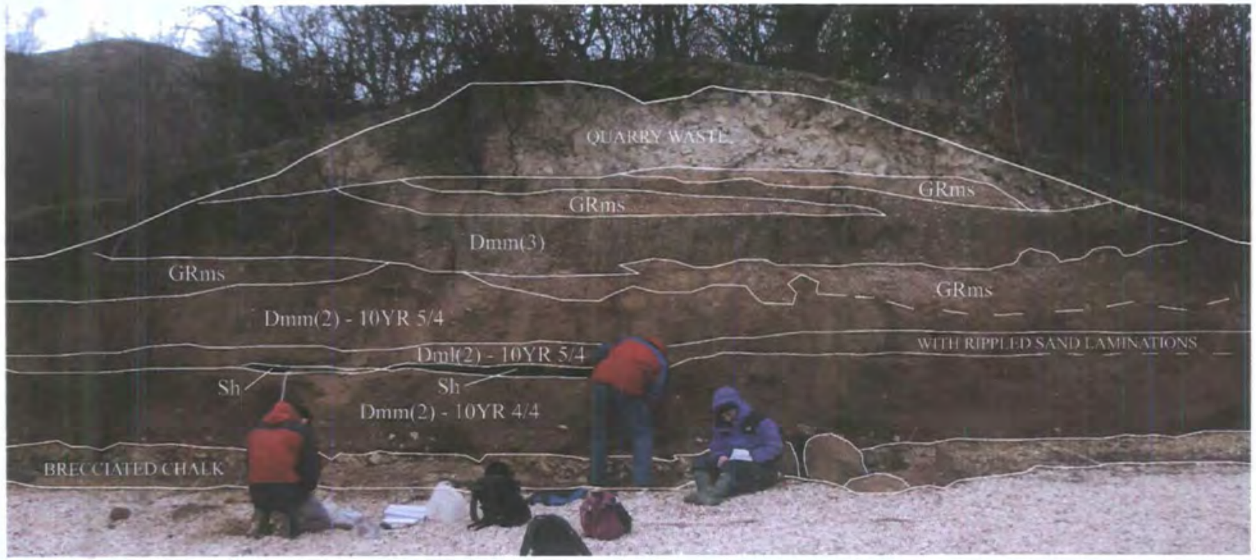
Facies 5 (FF5) (Site 1) – Facies 5 is a laminated, clast-rich diamicton which is lighter than Facies 4 (10YR 4/4). Laminations are dense, continuous and are made of primarily sand with some clay.

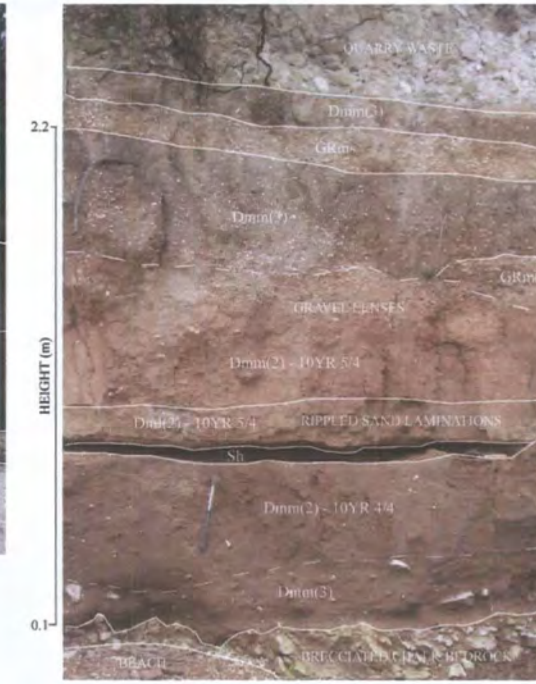
Facies 6 (FF6) (Site 1) – Comprises of a massive, red-brown (7.5YR 3/3), clast-rich diamicton. This unit is also interrupted by isolated sand laminations and sections of a sandy-clay diamicton of different texture to the main diamicton body.

Facies 7 (FF7) (Site 2) – Consists of a massive, orange-brown (5YR 4/3), clast-rich diamicton. The diamicton is coarser than facies lower down in the sequence and is clearly weathered.

4.2.4 South Ferriby (SE 998225)

The two sites studied at South Ferriby are located on the south bank of the River Humber, about 1km north-east of South Ferriby village. At Site 1 (Figure 4.34), dark brown (10YR 4/4) massive diamicton (Facies 1), 0.7m thick rests unconformably on brecciated chalk bedrock. An increased concentration of clasts is evident in the lower 0.2m of the unit, increasing the concentration of chalk clasts in this section, compared to higher up in the unit, and the section as a whole. Flint, limestone and sandstone are also present and can be found throughout the section. A thin, discontinuous, laminated sand





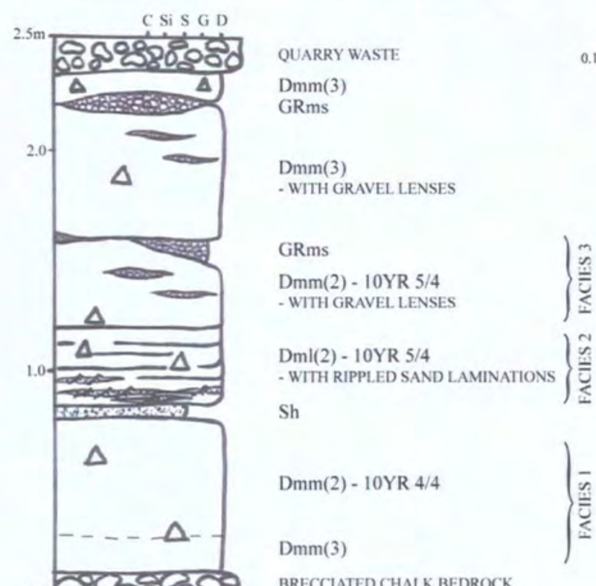


Figure 4.34. Site 1, South Ferriby. Clockwise from top left: annotated photograph; Site 1 close-up; section log; sample locations. Geological hammer for scale.

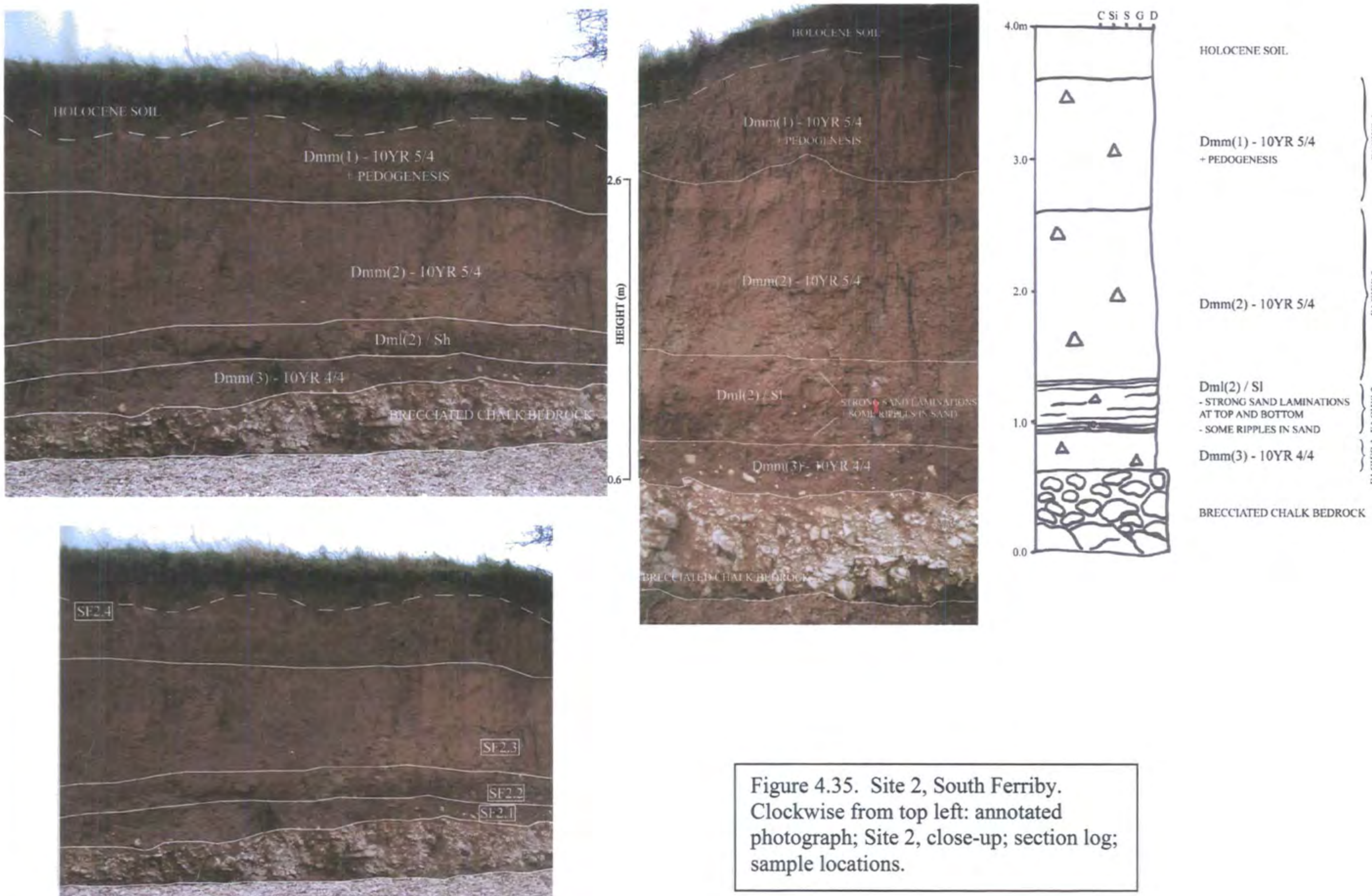


Figure 4.35. Site 2, South Ferriby. Clockwise from top left: annotated photograph; Site 2, close-up; section log; sample locations.

unit, no more than 15cm thick, separates Facies 1 from a laminated diamicton unit above (Facies 2). The laminated diamicton is much lighter than Facies 1 (10YR 5/4), and contains discontinuous rippled sand laminations 1-1.5cm thick. Above Facies 2 lies another unit of massive diamicton (Facies 3), also of Munsell colour 10YR 5/4. The diamicton appears much sandier than Facies 1 and contains abundant gravel lenses towards the top of the 0.4m section. Discontinuous beds of matrix-supported gravel occur above this unit, followed by a darker, massive diamicton, rich in angular chalk clasts. A substantial matrix-supported gravel lens also lies within this diamicton. Quarry waste caps the sequence. Two samples were taken from Facies 1, one from the Facies 2, and one from the Facies 3 (Figure 4.34).

Site 2 (Figure 4.35) is located 90m east of Site 1 and exhibits a very similar sequence. A dark brown (10YR 4/4), massive diamicton (Facies 1), again rests on brecciated chalk bedrock, where more clasts are also evident in the basal layers. Here the whole unit is 0.3m thick. A 0.4m thick laminated diamicton (Facies 2) appears above it where laminations are caused by discontinuous lenses of sand, some containing ripple structures. The unit is demarcated by strong, continuous sand laminations at the top and bottom, where these sand layers also contain ripple structures. The remainder of the section consists of a light brown (10YR 5/4) massive diamicton (Facies 3) containing less clasts than Facies 1. The upper 1m of the section (Facies 4) is clast-poor and weathered, showing signs of pedogenesis and contains no chalk clasts. No colour change is apparent between the weathered and unweathered diamictons however. Four samples were taken at this site from Facies 1-4 (Figure 4.35).

Facies Association Summary

Facies 1 (SFF1) (Sites 1 & 2) – Consists of a dark brown (10YR 4/4), massive diamicton. There is a moderate to high abundance of clasts within this unit, which consist predominantly of chalk, followed by flint, limestone and sandstone.

Facies 2 (SFF2) (Sites 1 & 2) – This unit consists of a diamicton containing densely packed, discontinuous, sand laminations. Ripple structures within the sand laminations are clearly visible and the whole unit is much lighter than Facies 1 (10YR 5/4).

Facies 3 (SFF3) (Sites 1 & 2) – Facies 3 is a unit of massive diamicton of the same colour as Facies 2 (10YR 5/4). Compared to Facies 1, the matrix of the diamicton is much coarser and generally contains less clasts.

Facies 4 (SFF4) (Site 2) – Comprises of a clast-poor, massive diamicton (10YR 5/4), of which there are virtually no chalk clasts. The unit has been extensively weathered and displays signs of pedogenesis.

4.2.5 Kirmington (TA 103117)

The site at Kirmington is an excavation in a woodland bank just north of the village of Kirmington. At the base of the section lie horizontally bedded gravels interrupted by a sand layer 0.15m thick. A 1.3m thick unit of diamicton (Facies 1) rests above these gravels. The diamicton is dark brown (10YR 4/2), and becomes increasingly weathered in the upper 0.85m of the unit, where pedogenesis has occurred. Small chalk clasts are abundant towards the base, but are less frequent in the weathered section (Facies 2). Other clasts found in the section include flint, sandstone, limestone, porphyry and quartzite. A small dark band (10YR 3/1) was apparent in the basal layers, but after further excavation it became less obvious. Samples K1.1-K1.3 were taken from this diamicton (Figure 4.36).

Facies Association Summary

Facies 1 (KF1) – Consists of a dark brown (10YR 4/2), massive diamicton, which contains clasts such as chalk, sandstone, limestone, flint, porphyry and quartzite.

Facies 2 (KF2) – Facies 2 is a weathered version of Facies 1, which displays signs of pedogenesis and contains far fewer chalk clasts.

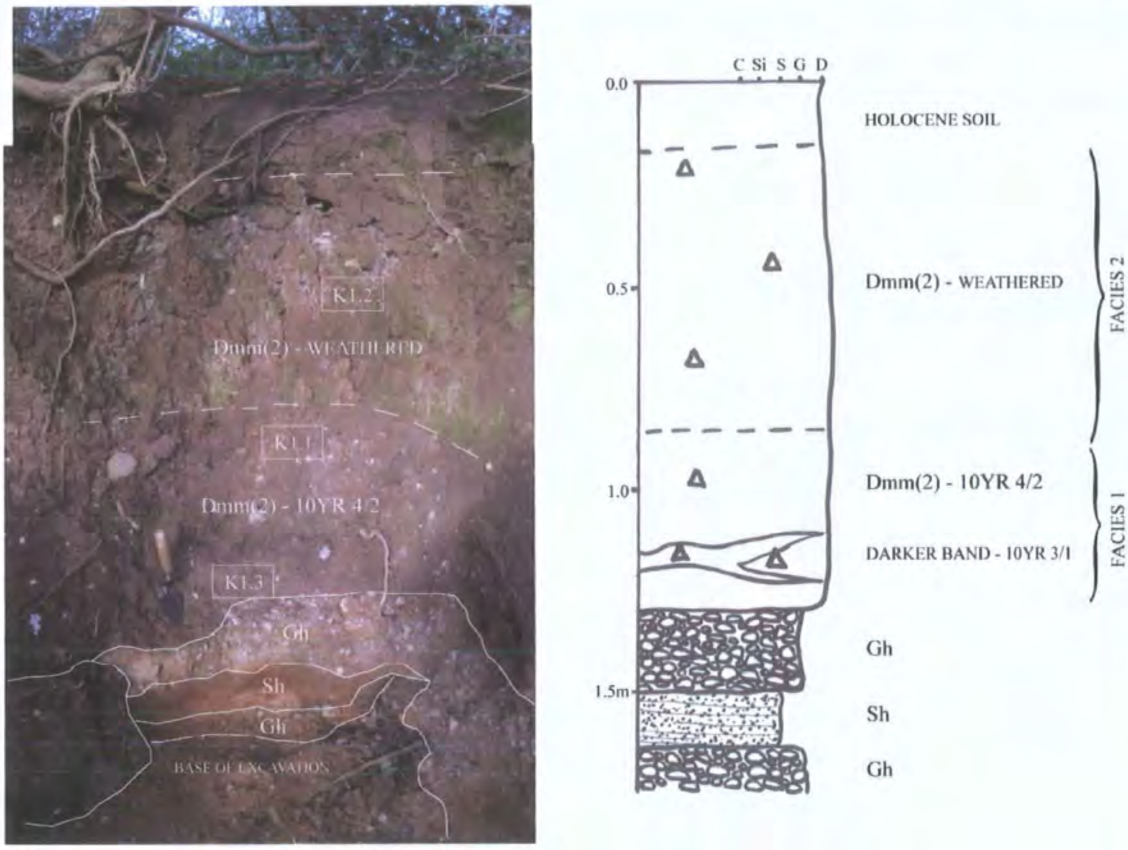


Figure 4.36. Kirmington; section log and sample locations. Trowel for scale.

4.2.6 Welton-Le-Wold (TF 284882)

Two quarries located north-east of the village of Welton-Le-Wold contain sediments, which have been classified as the Welton, Calcethorpe and Marsh Tills (Straw, 1969). The area is important since it is located at the maximum position that the Late Devensian British Ice Sheet reached inland in Lincolnshire, depositing the Marsh Till. Research was undertaken at the eastern quarry where the Devensian till succession rests upon the Pre-Devensian Welton Till. The Welton Till consists of a light brown, clast-rich diamicton, which contains a significant proportion of chalk clasts. The other pre-Devensian till, the Calcethorpe Till, is absent at this site, in contrast to its presence at another quarry in close proximity (Figure 4.38).

An extensive dark brown, fine-grained diamicton (Facies 1) (10YR 4/2) occurs at the base of the Devensian sequence (Figure 4.37). Sample W1.1 was taken from this unit where it begins to become mixed with the overlying massive diamicton (Facies 2). This diamicton is about 4.5m thick, clast-rich, although containing less clasts than the underlying Welton Till and redder than the underlying unit (10YR 4/3). Samples W1.2 to W1.6 were collected upwards in the main diamicton. Evidence of weathering and slumping occurs towards the top of the section (Facies 3). Clasts found within the section include chalk, flint, sandstone, limestone, and some porphyry, quartz, shale and coal.

Facies Association Summary

Facies 1 (WF1) – Consists of dark brown (10YR 4/2), clast-poor, massive diamicton, finer in texture than the overlying Facies 2. The boundary between Facies 1 and 2 is indistinct, where portions of Facies 1 have been incorporated into Facies 2.

Facies 2 (WF2) – Comprises of a clast-rich, massive diamicton, which is redder (10YR 4/3) than Facies 1. It contains predominantly, chalk, flint, sandstone and limestone along with some porphyry quartz, shale and coal.

Facies 3 (WF3) – Facies 3 is a weathered form of Facies 2, consisting of massive diamicton at the top of the sequence.

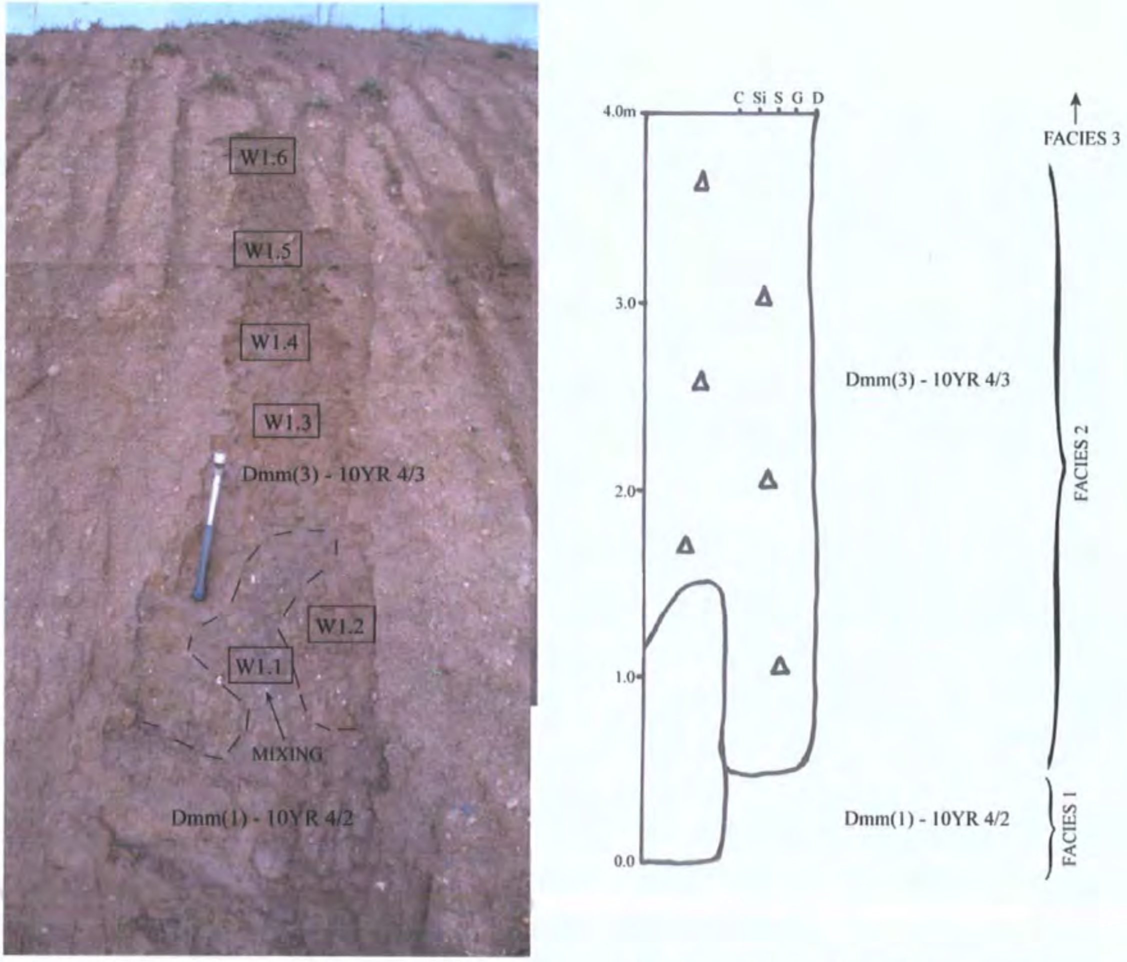


Figure 4.37. Welton-Le-Wold; section log and sample locations. Geological hammer for scale.

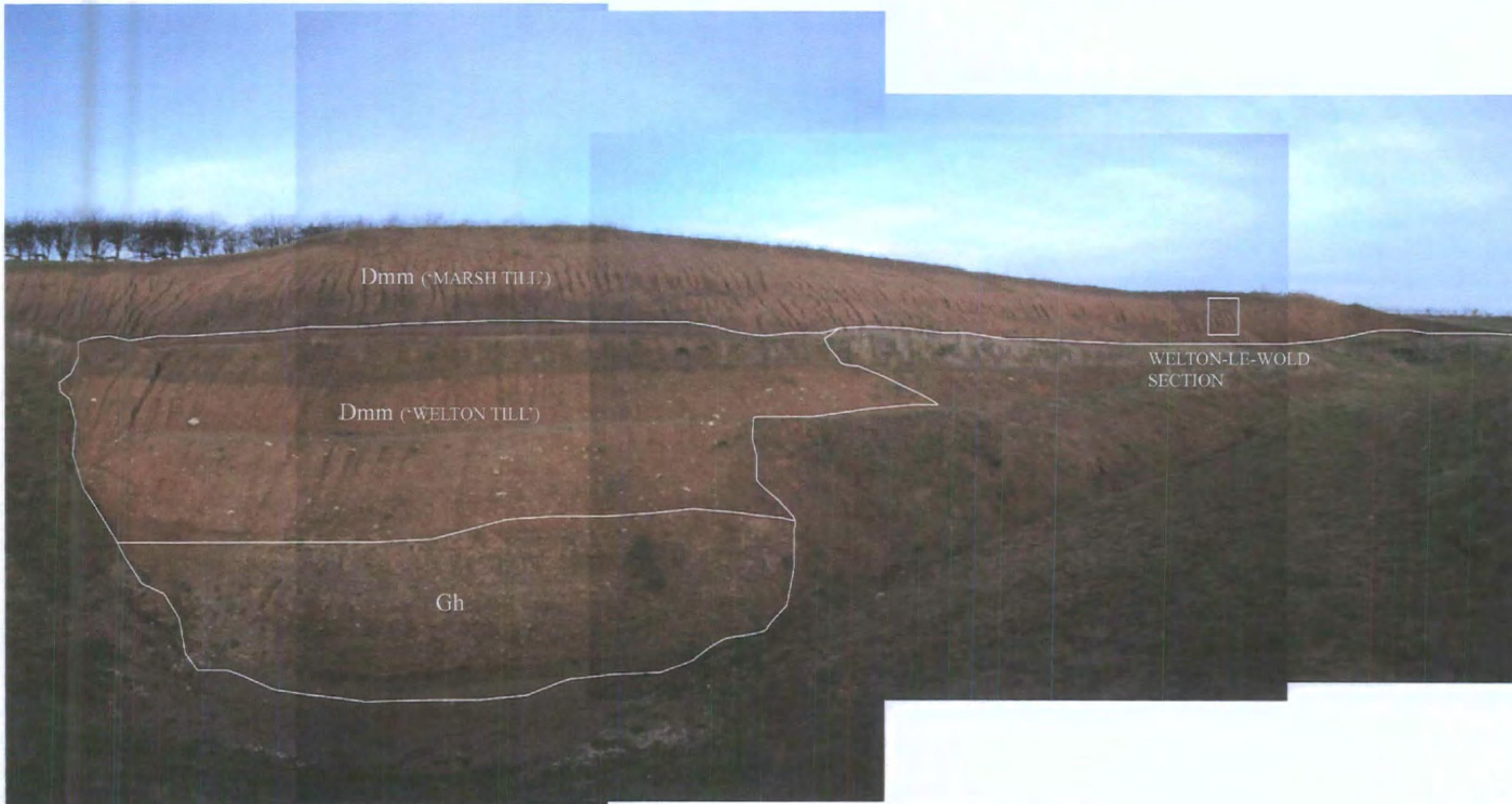


Figure 4.38. Welton-Le-Wold overview.

4.2.7 Morston (TF 986440)

The excavation at Morston (Figure 4.39) is found at the southern edge of the Stiffkey Salt Marshes, west of the village of Morston. A thin bed of horizontally bedded sands and gravels lies beneath a 1m thick unit of horizontally bedded gravels. Above these gravels rests a thin unit of massive diamicton with a maximum thickness of 1m. The diamicton is a sandy, reddish brown (7.5YR 4/3) colour and can be divided into two sub-units separated by a gradational boundary. Facies 1 is very clast-poor, and contains few clasts over 4mm in size. The upper unit (Facies 2) is much richer in clasts (predominantly sandstone, limestone and flint) by comparison and appears very slightly darker in colour, although this could be due to a higher moisture content.

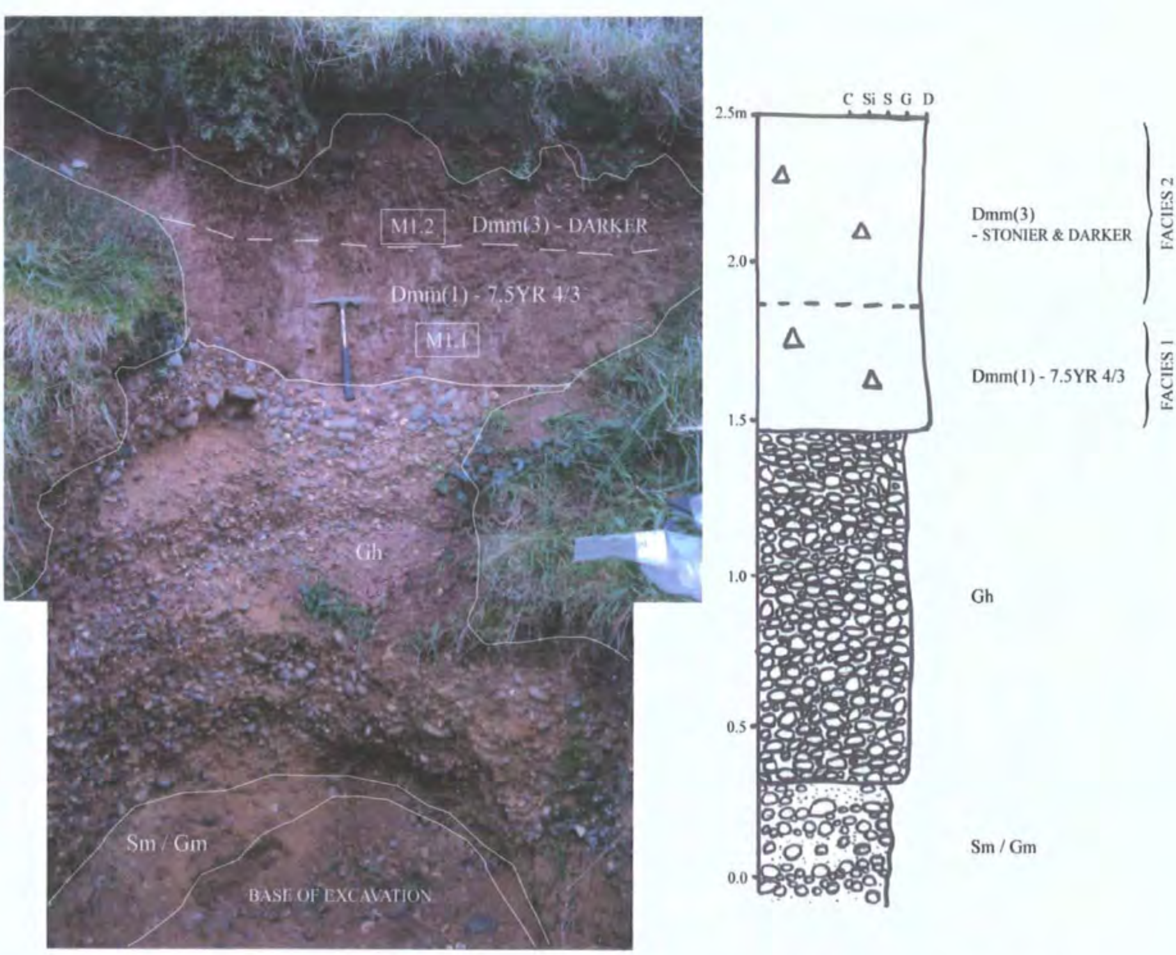


Figure 4.39. Morston; section log and sample locations. Geological hammer for scale.

Facies Association Summary

Facies 1 (MF1) – This unit contains clast-poor, sandy, reddish-brown (7.5YR 4/3), weathered, massive diamicton which contains few clasts over 4mm.

Facies 2 (MF2) – Also comprises of sandy, reddish-brown (7.5YR 4/3), weathered, massive diamicton, but is much richer in clasts (sandstone, limestone and flint).

4.3 Geochemical Analysis

4.3.1 Dimlington

Complete Linkage

Using combined z-scores, the complete linkage dendrogram for Dimlington produced seven groups at a Euclidean distance of 10 or less, named CT-CZ (Figures 4.40 & 4.42). Three samples labelled CX1, CW1 and CV1 were not assigned to groups at this level of similarity. In general, cluster groups appear to be defined by the amount of chalk and limestone within the samples, where groups CT-CW represent samples generally containing higher amounts of chalk, and are often lighter in colour than groups CX-CZ. All the weathered diamictons from Sites 1 and 5 (Facies 8) cluster together in group CZ, but they also cluster with the lower diamicton at Site 6 (Facies 10) and the dark, chalk-poor diamictons at Sites 2, 3, and 4 (Facies 2). This indicates that changes due to weathering are not influential enough to define a separate group, although the most influential factor combining these samples could be their lack of chalk. However, Figure 4.44 shows that the signal is much more complicated than this, where although groups CT and CW contain high abundances of calcium (Ca) and its associated trace element Sr, groups CU and CV contain similar amounts of Ca and Sr to groups CY and CZ, whilst group CX has a much higher Ca and Sr content. Abundances of other elements in these groups show that groups CX, CY and CZ contain higher abundances of a number of elements, e.g. Ti, Fe, Li, Be, Ba, V, Cr, Co, Ni, Cu, Zr, Nb and U, thus explaining why group CX clusters with groups CY and CZ despite different abundances of Ca and Sr (Figure 4.44).

The cluster dendrogram produced using individual z-scores also divided the samples into seven groups at a Euclidean distance of 10 or less, which are labelled CD1-CD7 (Figures 4.41 & 4.43). Four samples did not join a cluster at this similarity level, and are named CD8-CD11. Very few of the groups created using individual z-scores are identical to those created using the combined z-scores. Whilst the cluster groups, and how they cluster with one another change, it is possible to pick out mutual factors between the combined and individual z-score groupings. Table 4.1 indicates generally similar groups from the two methods. Dark brown/grey diamictons (Facies 2), with comparatively less chalk, tend to group in cluster CZ or CD1, whilst diamictons that are rich in chalk (e.g. Facies 1 and 3) are found in group CW or CD3. Samples which fall into groups CV, CX and CY, or CD2, CD4, or CD5 contain a suite of elements characteristic of both CZ and CW, or CD1 and CD3 and therefore changes in z-scores have placed different weight on different elements, causing the way in which these samples cluster to have changed.

Table 4.1. Comparison of Dimlington geochemical groups using complete linkage.

Combined z-scores	Individual z-scores
CT	CD6
CU	CD5
CV	CD2
CW	CD2 / CD3
CX	CD4
CY	CD2
CZ	CD1 / CD2

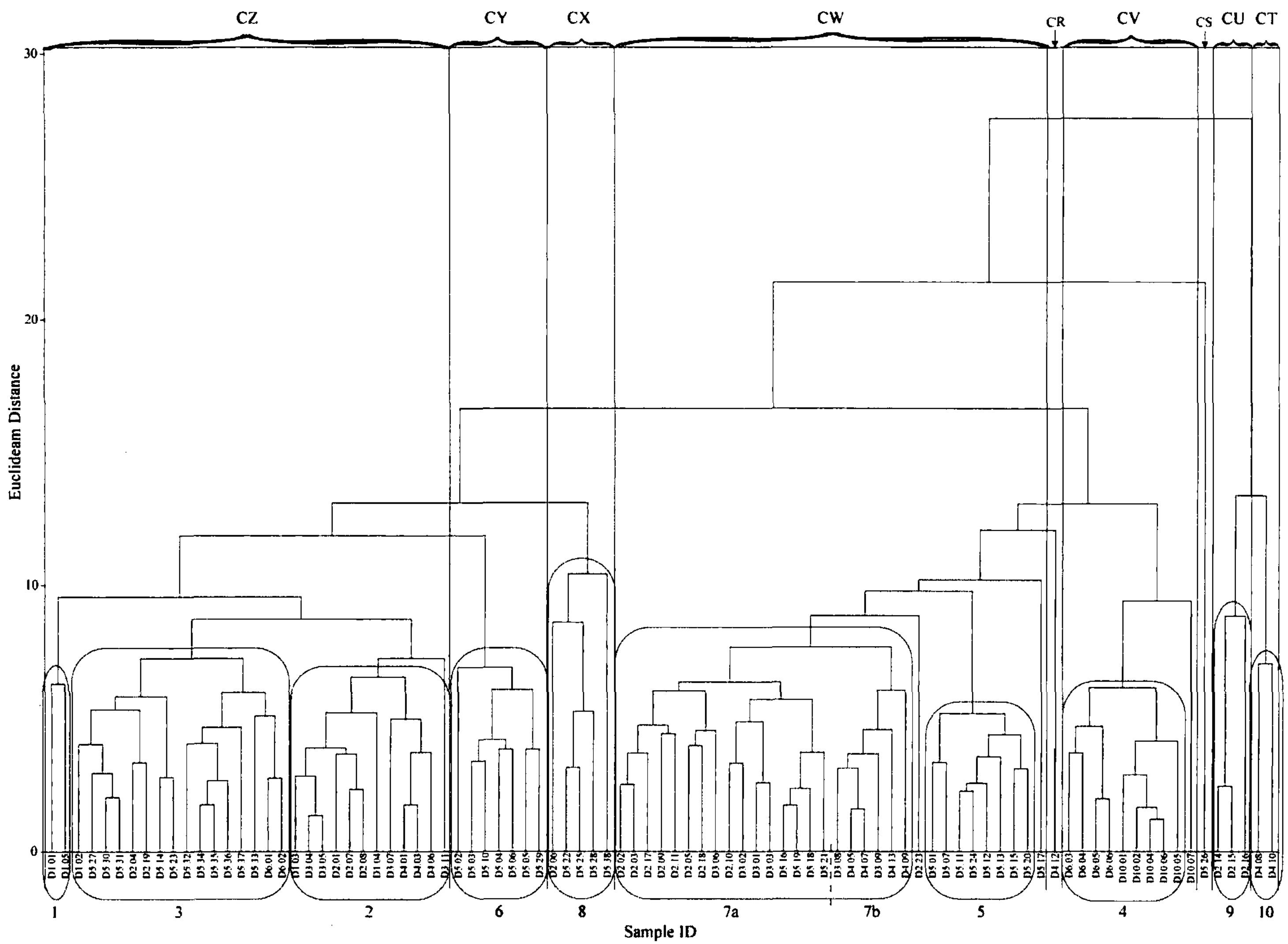


Figure 4.40. Dimlington diamicton, dendrogram of cluster analysis using complete linkage and combined z-scores, including geochemical groups (above) and ten overall groups for comparison with other methods.

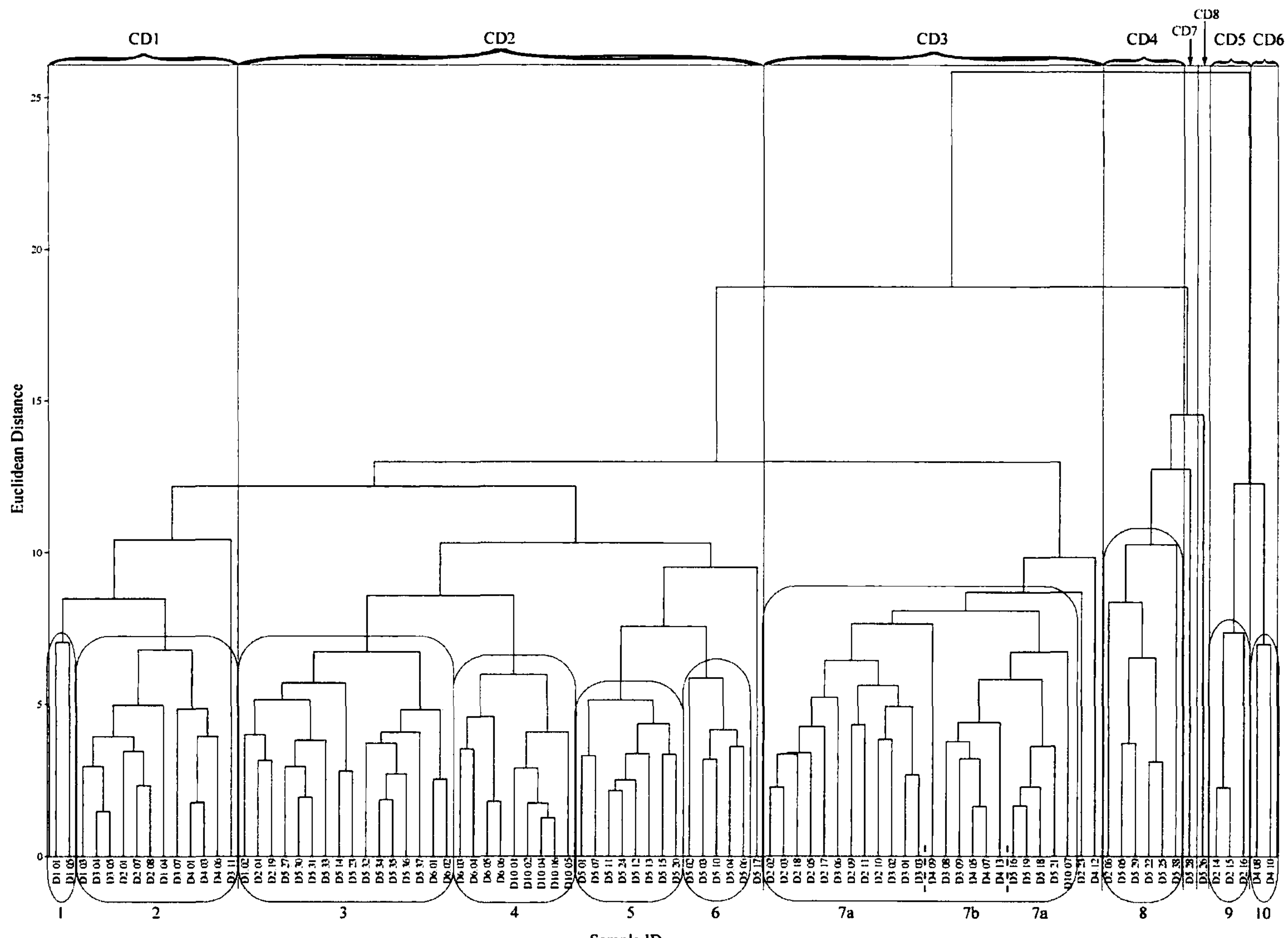


Figure 4.41. Dimlington diamicton, dendrogram of cluster analysis using complete linkage and individual z-scores, including geochemical groups (above) and ten overall groups for comparison with other methods.

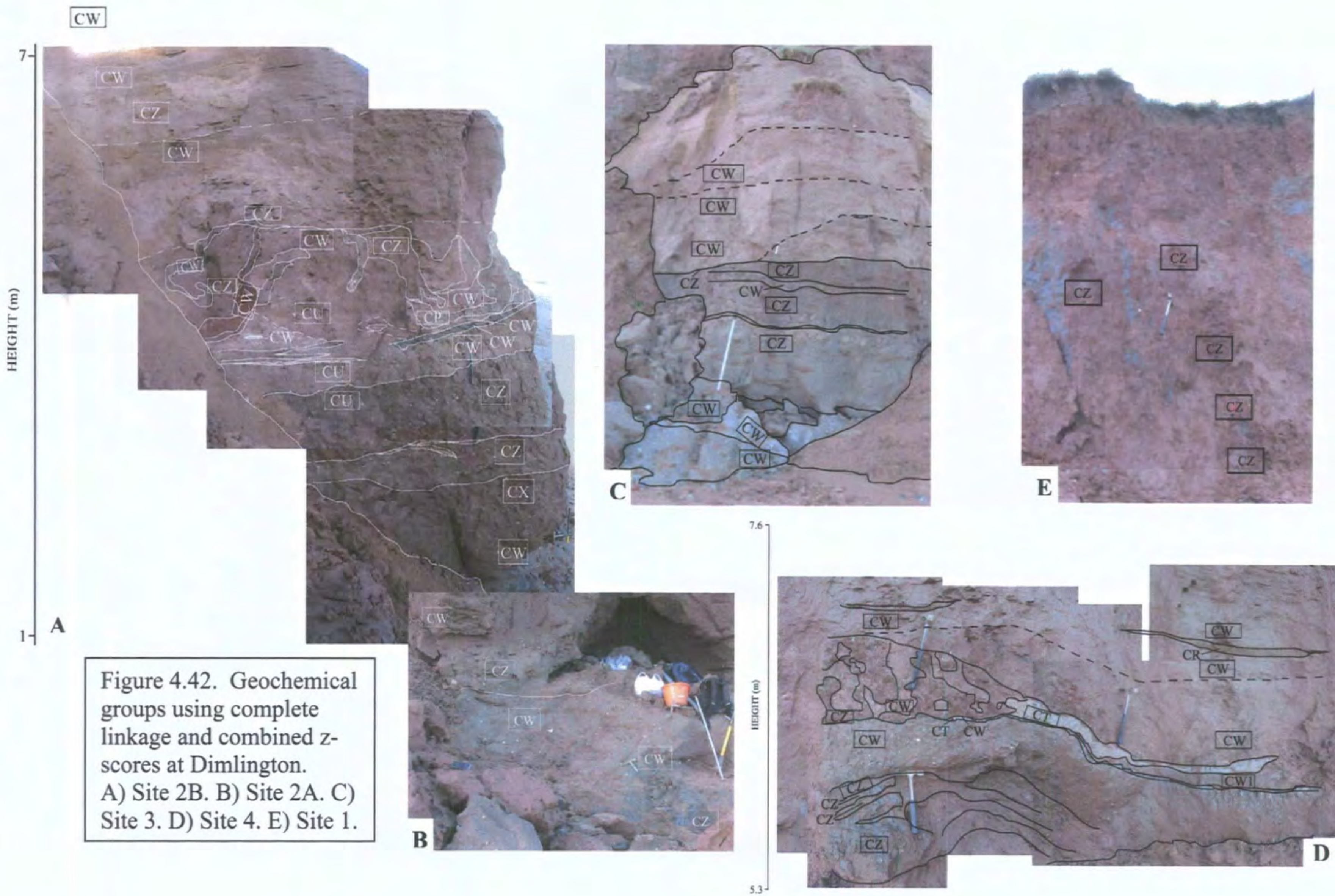
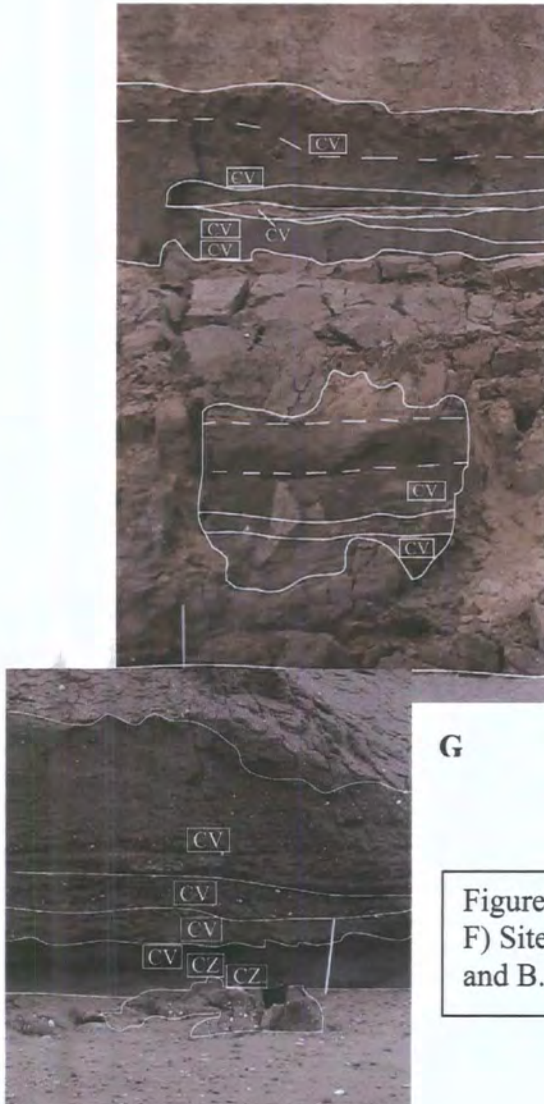


Figure 4.42. Geochemical groups using complete linkage and combined z-scores at Dimlington. A) Site 2B. B) Site 2A. C) Site 3. D) Site 4. E) Site 1.



G

J

I

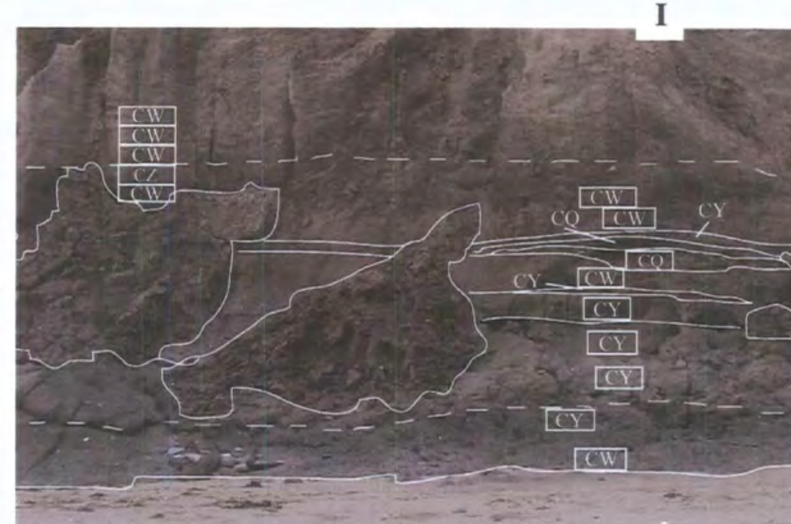


Figure 4.42 *continued.*
F) Site 6. G) Site 10. H) Site 5A and B. I) Site 5C. J) Site 5D.

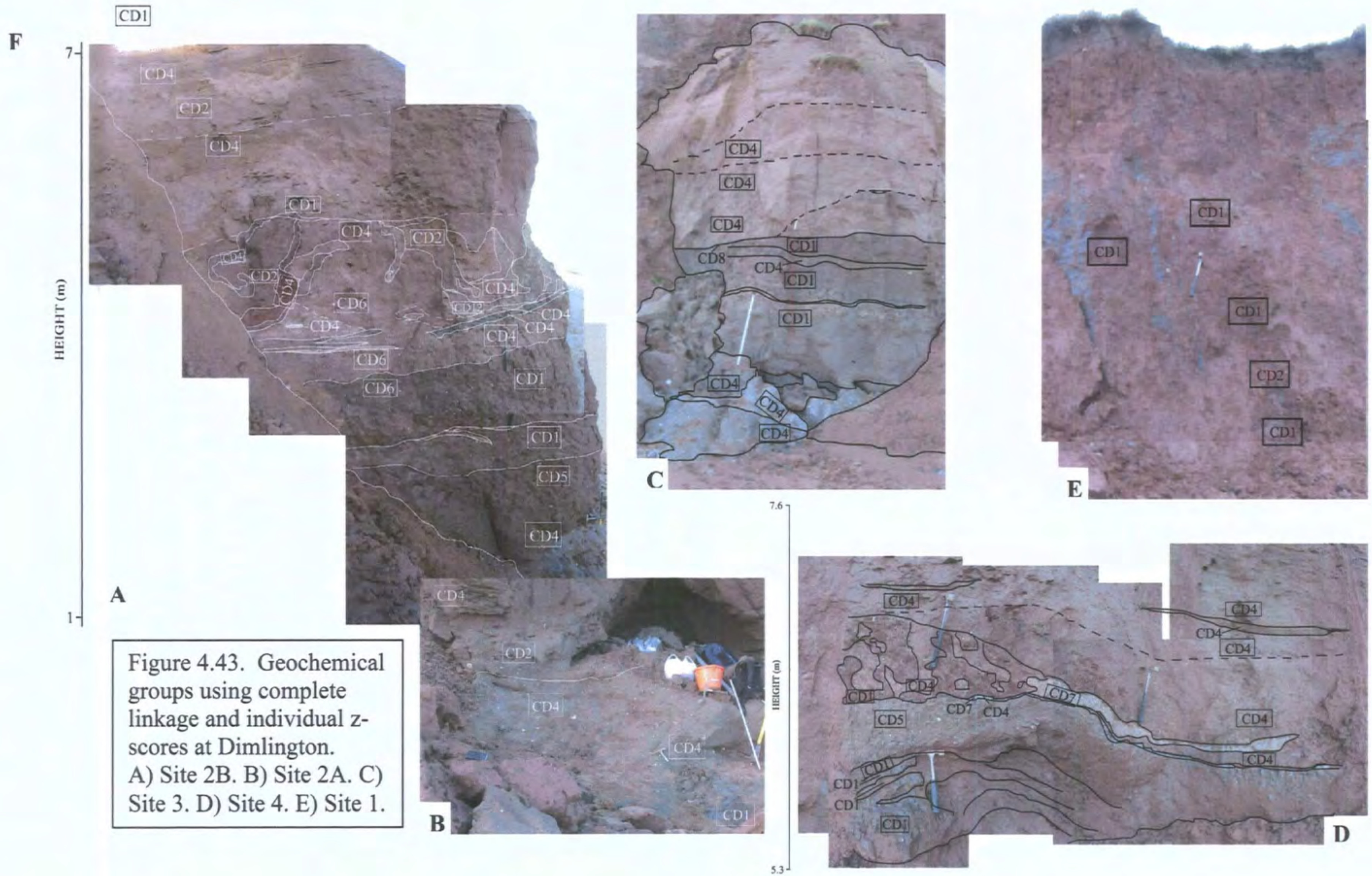
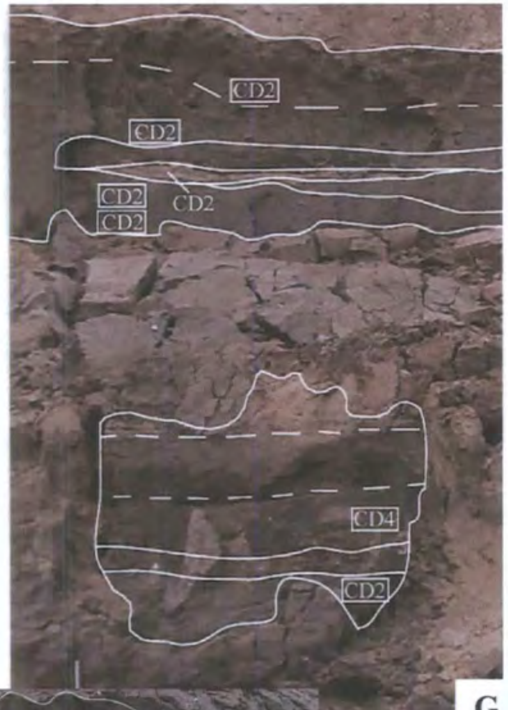


Figure 4.43. Geochemical groups using complete linkage and individual z-scores at Dimlington. A) Site 2B. B) Site 2A. C) Site 3. D) Site 4. E) Site 1.



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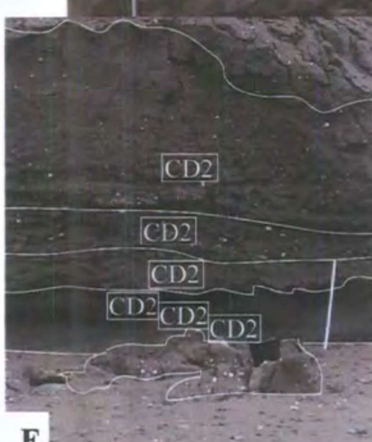


F

Figure 4.43 *continued.*
F) Site 6. G) Site 10. H) Site 5A and B. I) Site 5C. J) Site 5D.

H

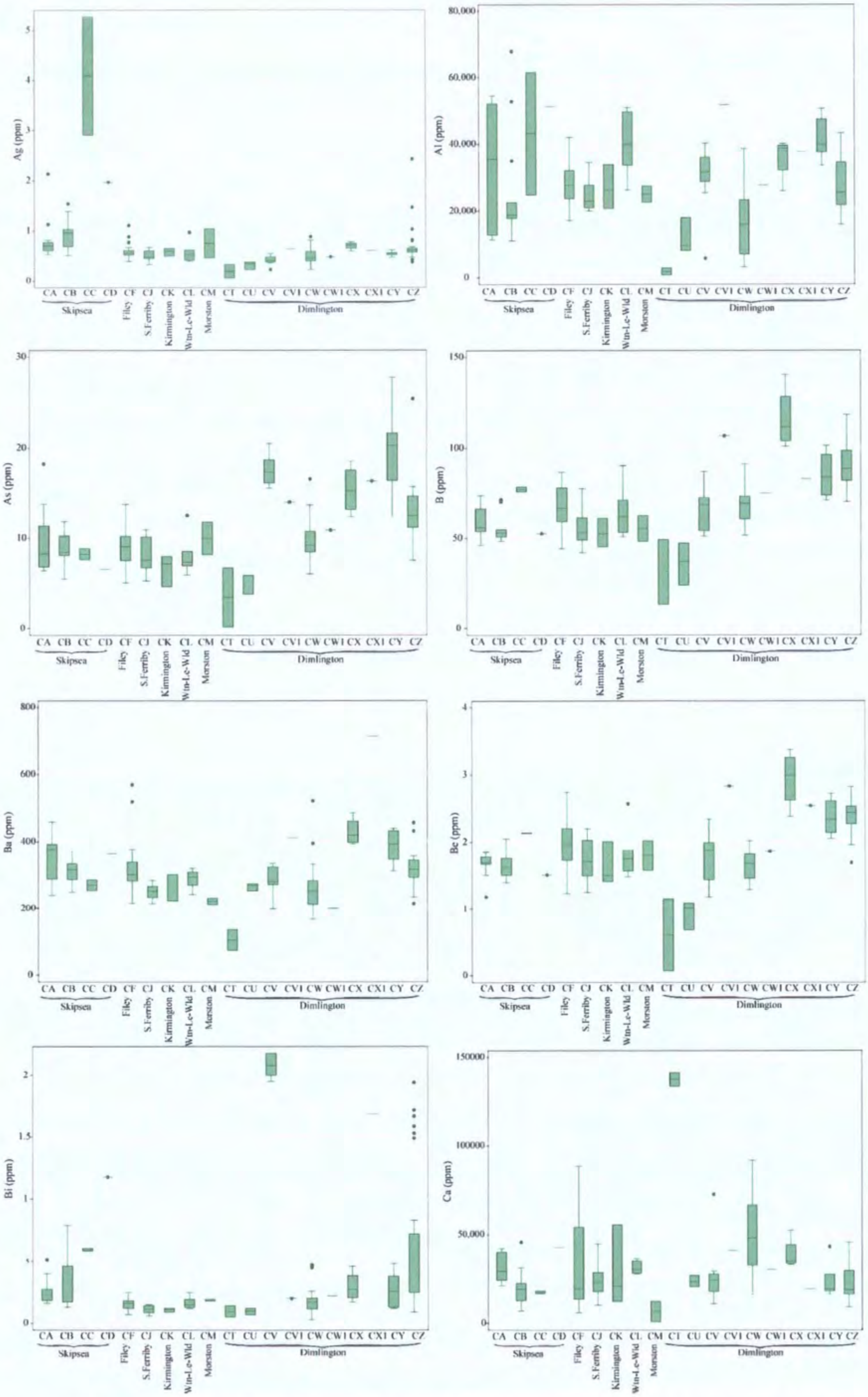


Figure 4.44. Element abundances within diamicton groups defined by complete linkage, combined z-score cluster analysis.

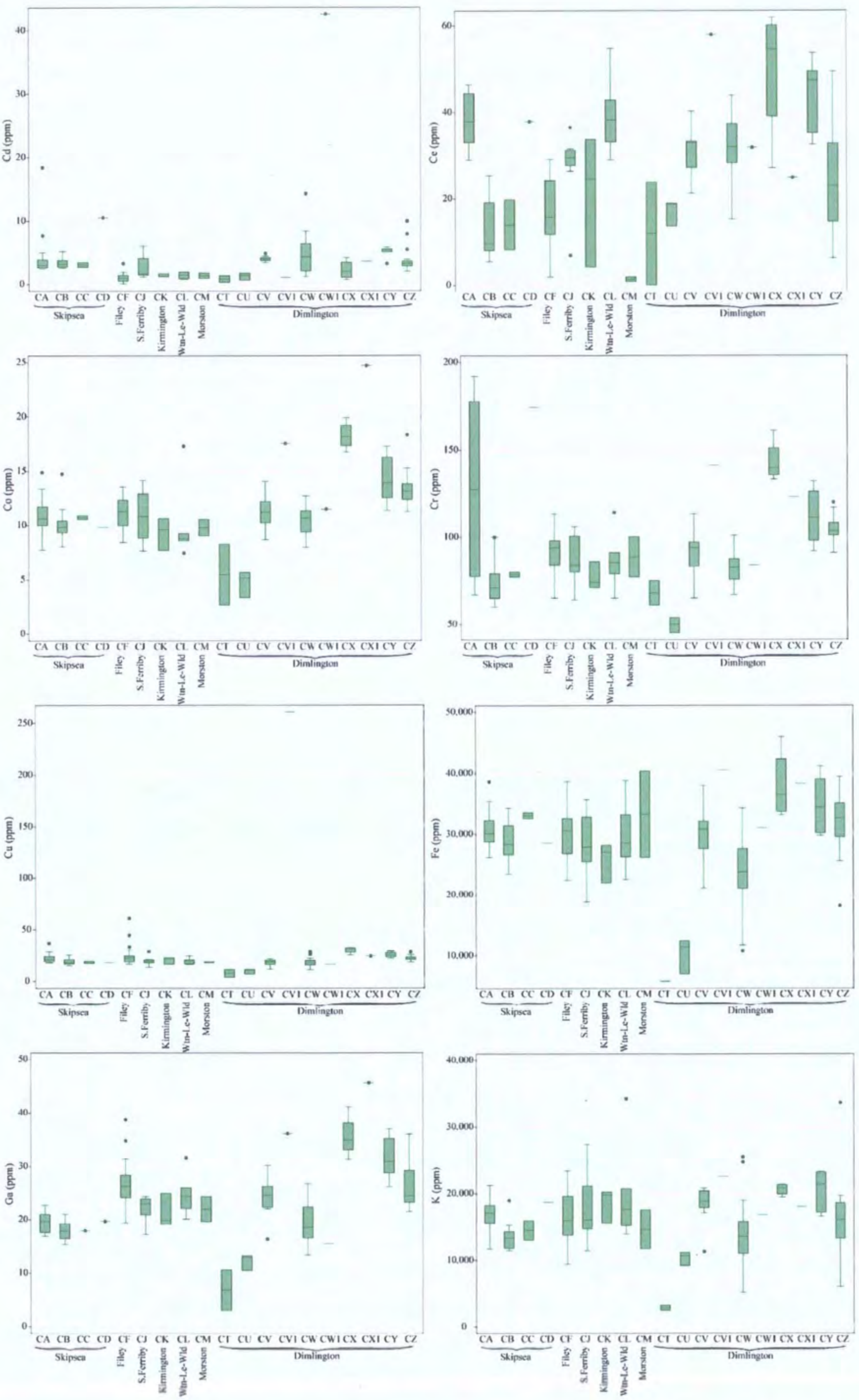


Figure 4.44 *continued.*

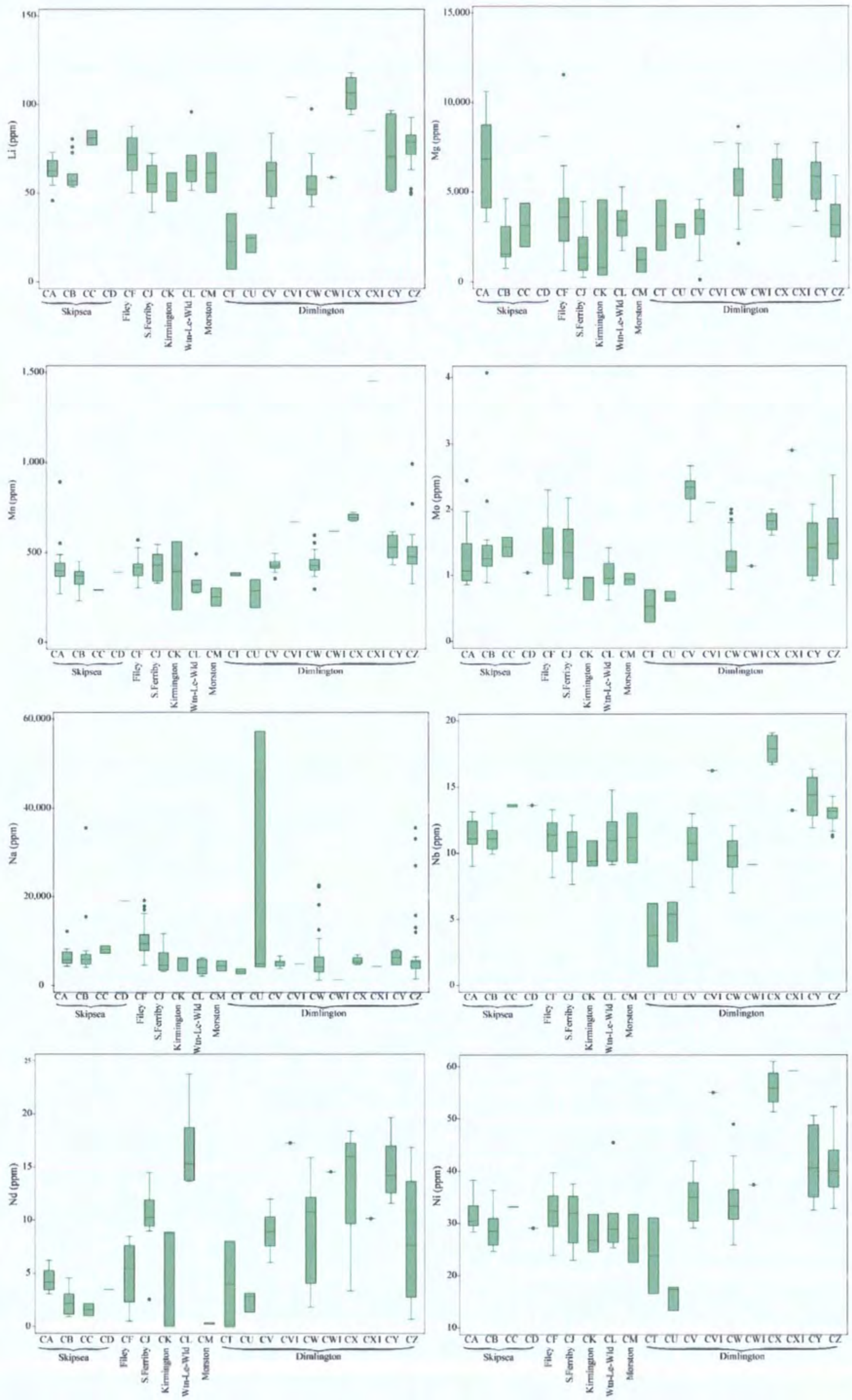


Figure 4.44 *continued.*

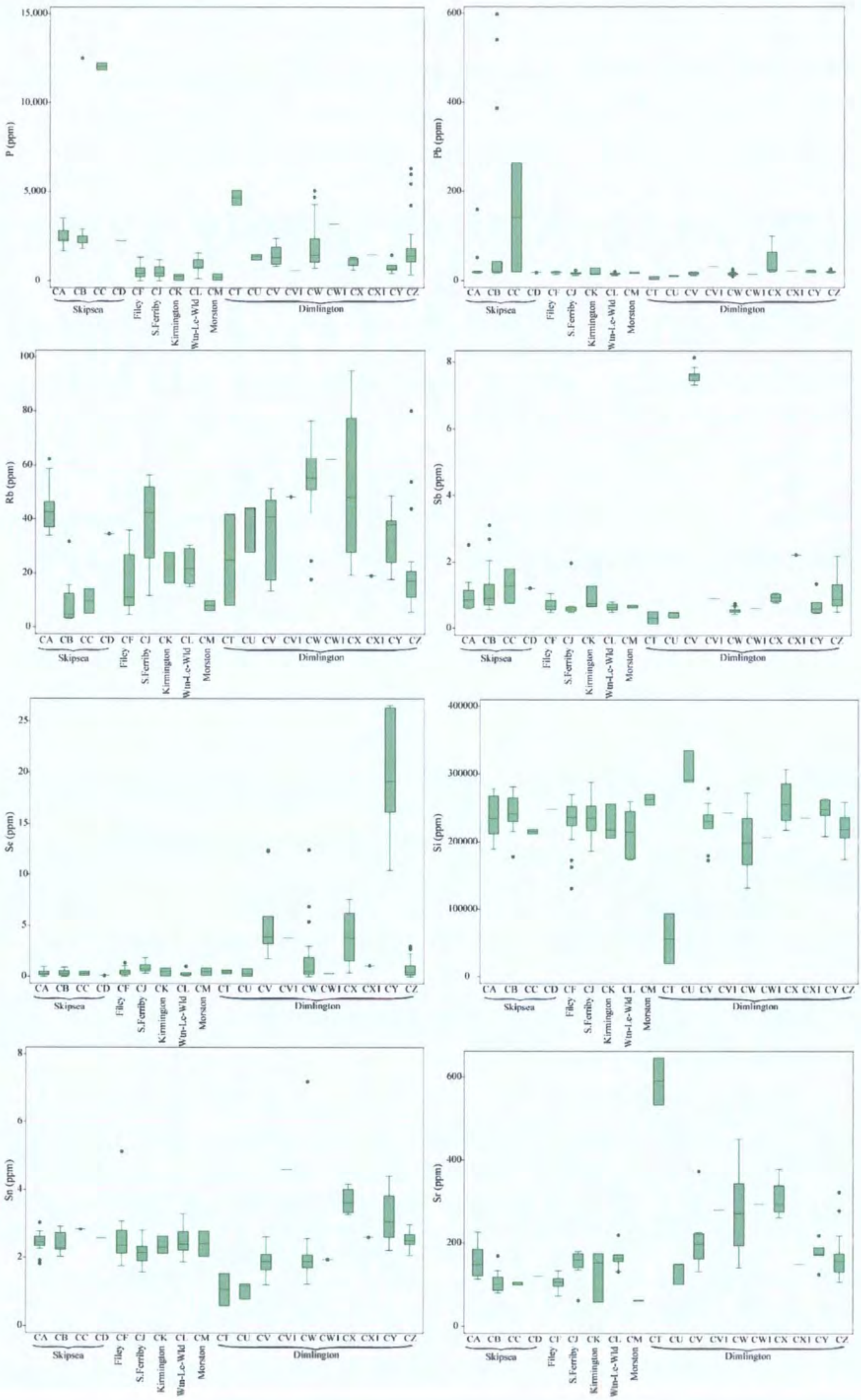


Figure 4.44 *continued.*

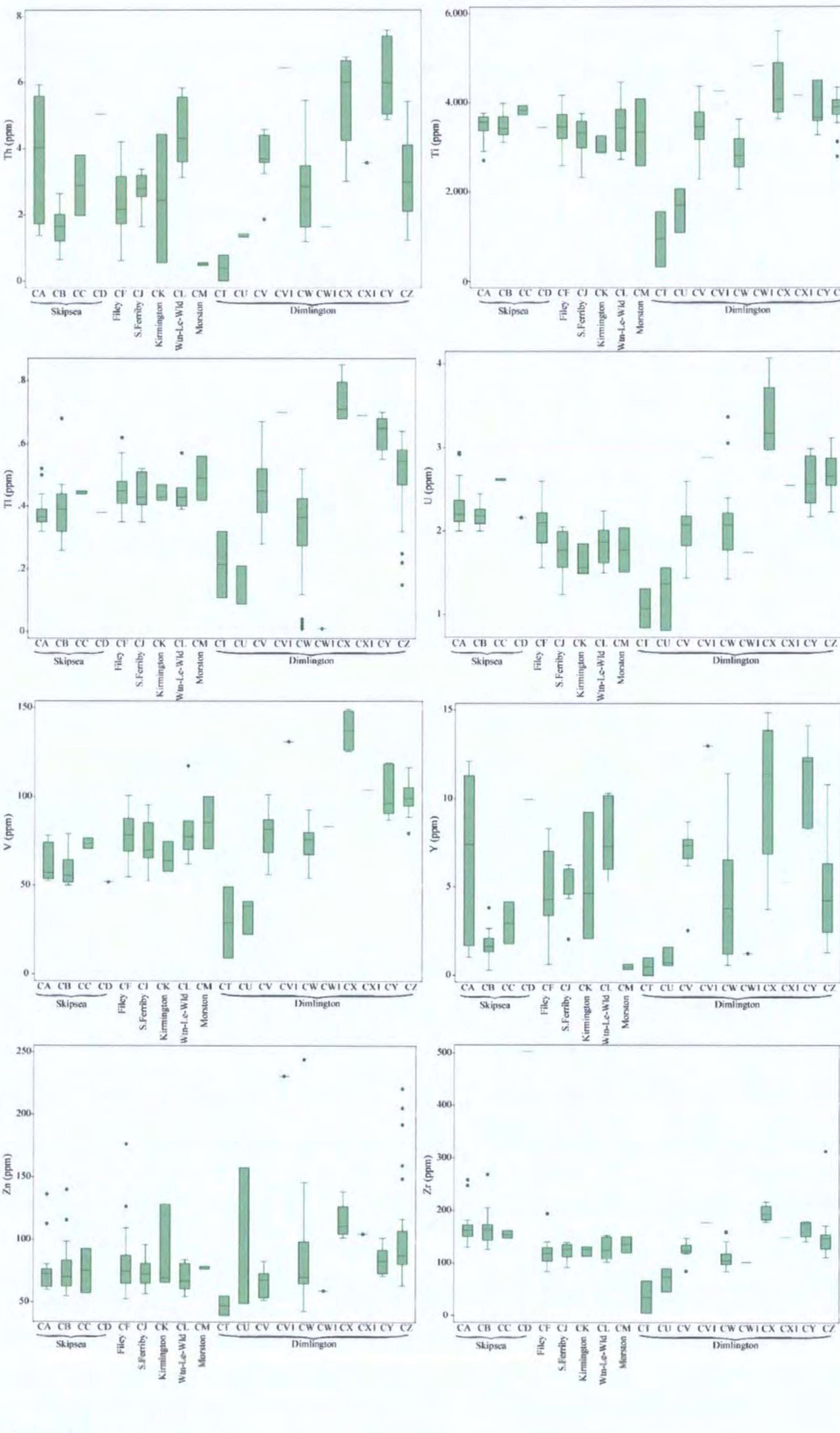


Figure 4.44 *continued.*

Figure 4.45. Element abundances within diamicton groups defined by complete linkage, individual z-score cluster analysis.

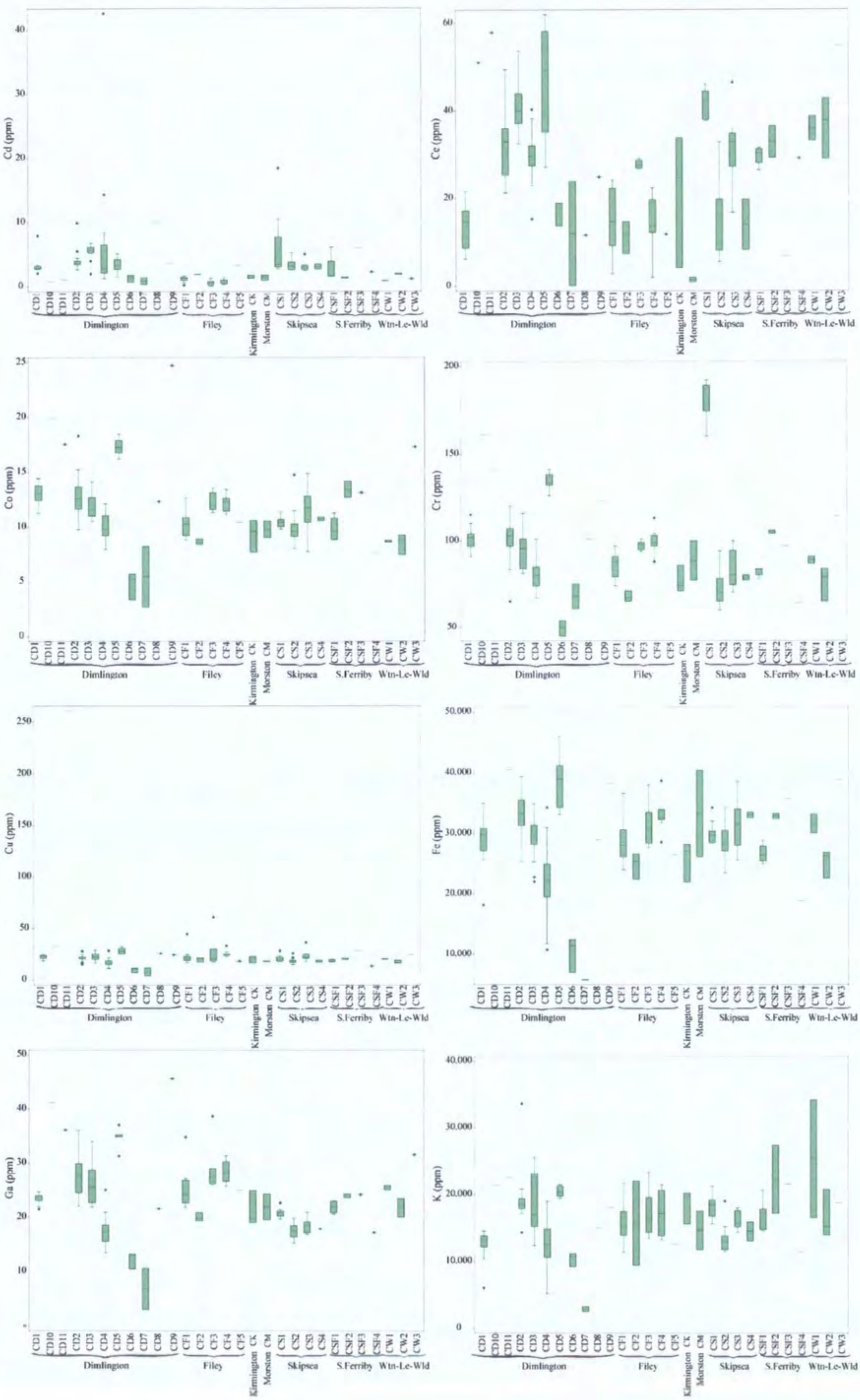


Figure 4.45 *continued.*

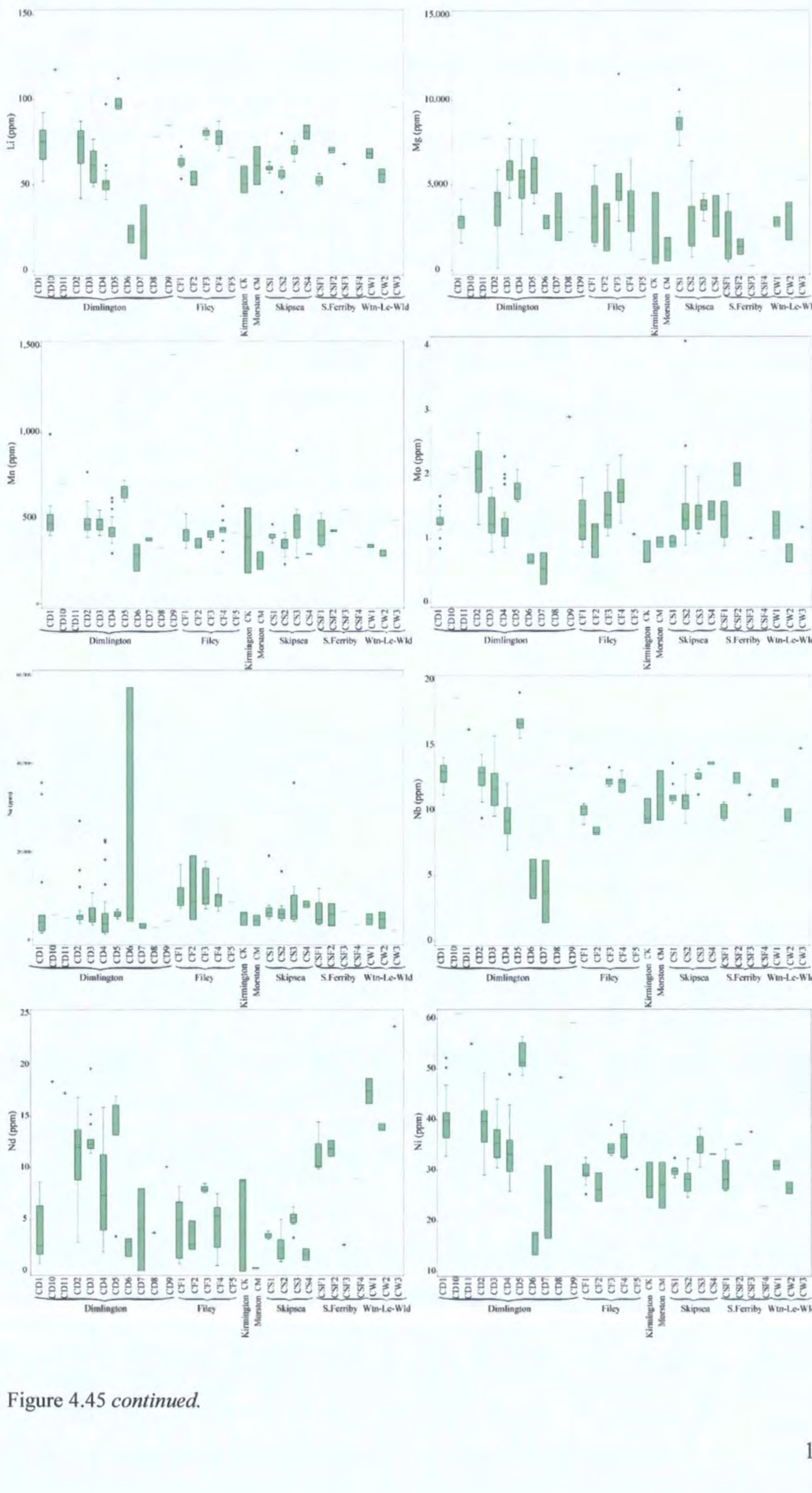


Figure 4.45 *continued.*

Figure 4.45 *continued.*

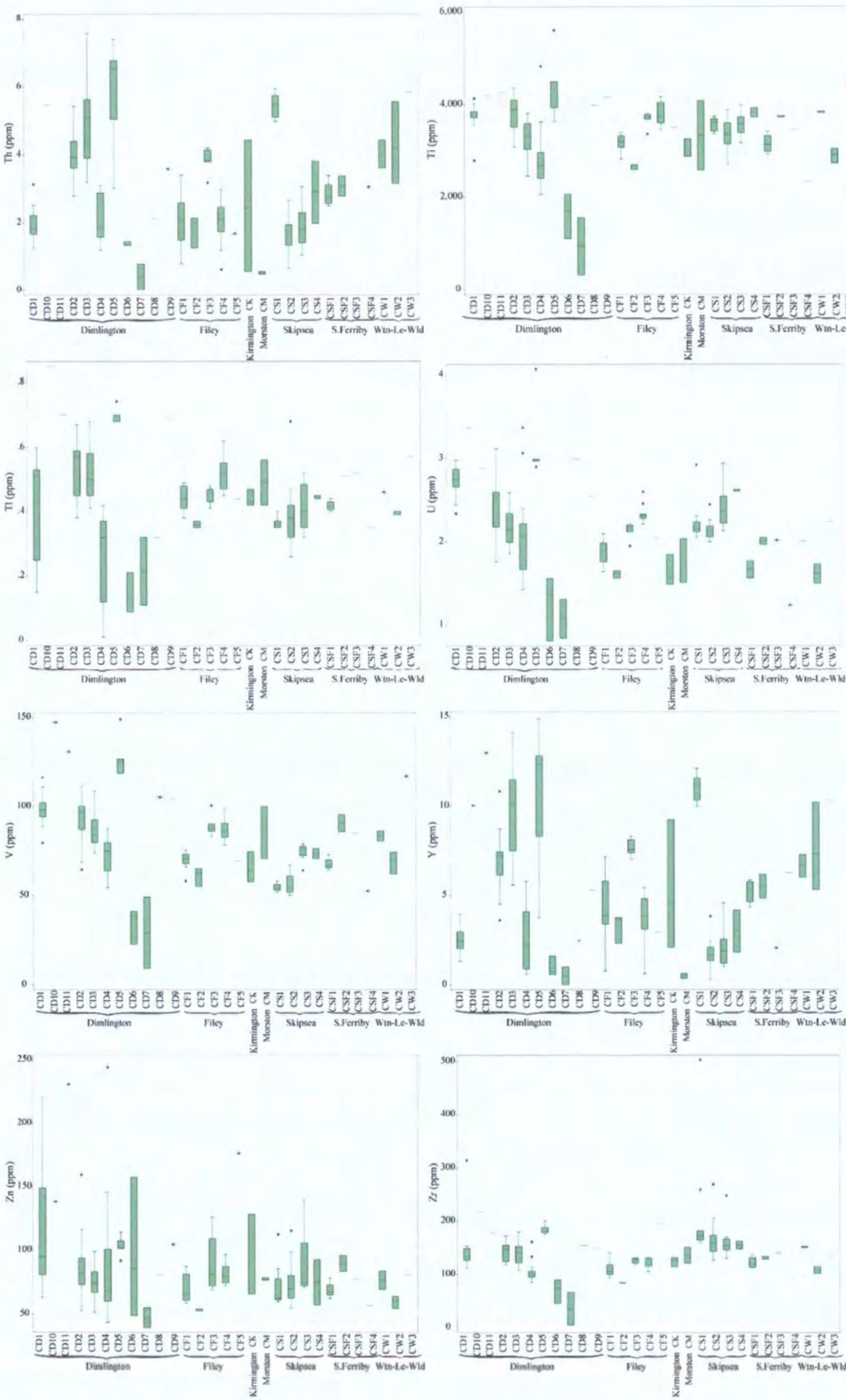


Figure 4.45 *continued.*

Ward's Method

From combined z-scores, using Ward's method, ten cluster groups were formed at a squared Euclidean Distance of 100 or less, and were named WQ-WZ (Figures 4.46 & 4.48). This left five samples remaining that did not join any of the clusters at this similarity level (WQ1, WST1, WS1, WP1, WX1). Cluster groups WQ-WZ can be divided into two main groups where WQ-WT represent the lighter, generally chalkier diamictons (Facies 1, 3 and some of 7), whilst WU-WZ correspond to any diamictons that contain less chalk and limestone. Once again, in groups WV (Facies 7, 8, 9) and WY (Facies 2 and 8), tills from the upper, red-brown, weathered sections in Site 1 and Site 5 (Facies 8) cluster with dark grey-brown diamictons in Sites 2, 3, 4 (Facies 2), and 6 (Facies 9), supporting the previous notion that variation in colour and degrees of weathering are not the most influential factors in the clustering.

Individual z-scores produced cluster groups containing similar sample assemblages to those formed using combined z-scores (Figures 4.47 & 4.49). However, the nature in which the clusters combine with other clusters is slightly different, where the groupings appear to be less influenced by the dominance of chalk and limestone. Again, ten cluster groups were produced below a squared Euclidean Distance of 100, with five samples unassigned to groups at this stage (Figure 4.47). The groups are named WD1-WD10, and the outlying samples labelled WD11-WD15. Table 4.2 shows how the groups compare to each other using the two methods. Whilst the majority of samples remain assigned to the same group, groups WD1 and WD2 are not equivalent to any cluster groups from the combined z-score dendrogram. However, samples within the combined WD1 and WD2 groups are almost exactly the same as the samples in groups WY and WZ.

The differences in the way the groups cluster together between the two methods highlights clusters that are most similar to each other. In this way, five main groups can be established. WD1 and WD2 (WY & WZ) represent the dark grey-brown diamictons at Sites 2, 3 and 4 (Facies 2) and the red-brown diamicton at Site 1 (Facies 8). WD3(WT) and WD4(WS) correspond to diamictons at Sites 2 and 3 which are predominantly dark in colour and rich in chalk clasts (Facies 1 and some Facies 3, although there are some exceptions at Site 2), as well as some samples from the middle section at Site 5 (Facies 7). WD5(WU) contains the brown upper diamicton at Site 6

(Facies 10), and all of the samples from Site 10 (Facies 2 and 11), with the exception D10.7, which only occurs in the WU cluster. WD6(WR) and WD7(WQ) correspond to the very light diamictons at Sites 2, 3 and 4 (Facies 3), which contain abundant amounts of chalk clasts. D10.7 is also included in this group using separate z-scores. The final group WD8(WX), WD9(WW) and WD10(WV) contains samples mainly from the lower and upper diamictons at Site 5 (Facies 5, 6, and 8) in addition to some samples from the middle of the Site 5 section (Facies 7) and the dark grey lower diamicton at Site 6 (Facies 9).

Table 4.2. Comparison of Dimlington geochemical groups using Ward's method.

Combined z-scores	Individual z-scores
WQ	WD7
WR	WD6
WS	WD4
WT	WD3
WU	WD5
WV	WD8/WD10
WW	WD9
WX	WD8
WY	WD1 / WD2
WZ	WD1 / WD2

Dimlington Overall

In order to facilitate comparison of the two methods, groups produced by the complete linkage method were sub-divided into clusters of samples that remained the same using both combined and separate z-scores. This produced ten groups shown in (Figures 4.40 & 4.41). With the exception of a few samples, all ten groups from the combined linkage method fell into the five groups produced by Ward's method (Figures 4.46 & 4.7), apart from group7, which is divided into 7a and 7b. Diamictons at Dimlington can therefore be assigned into five overall groups.

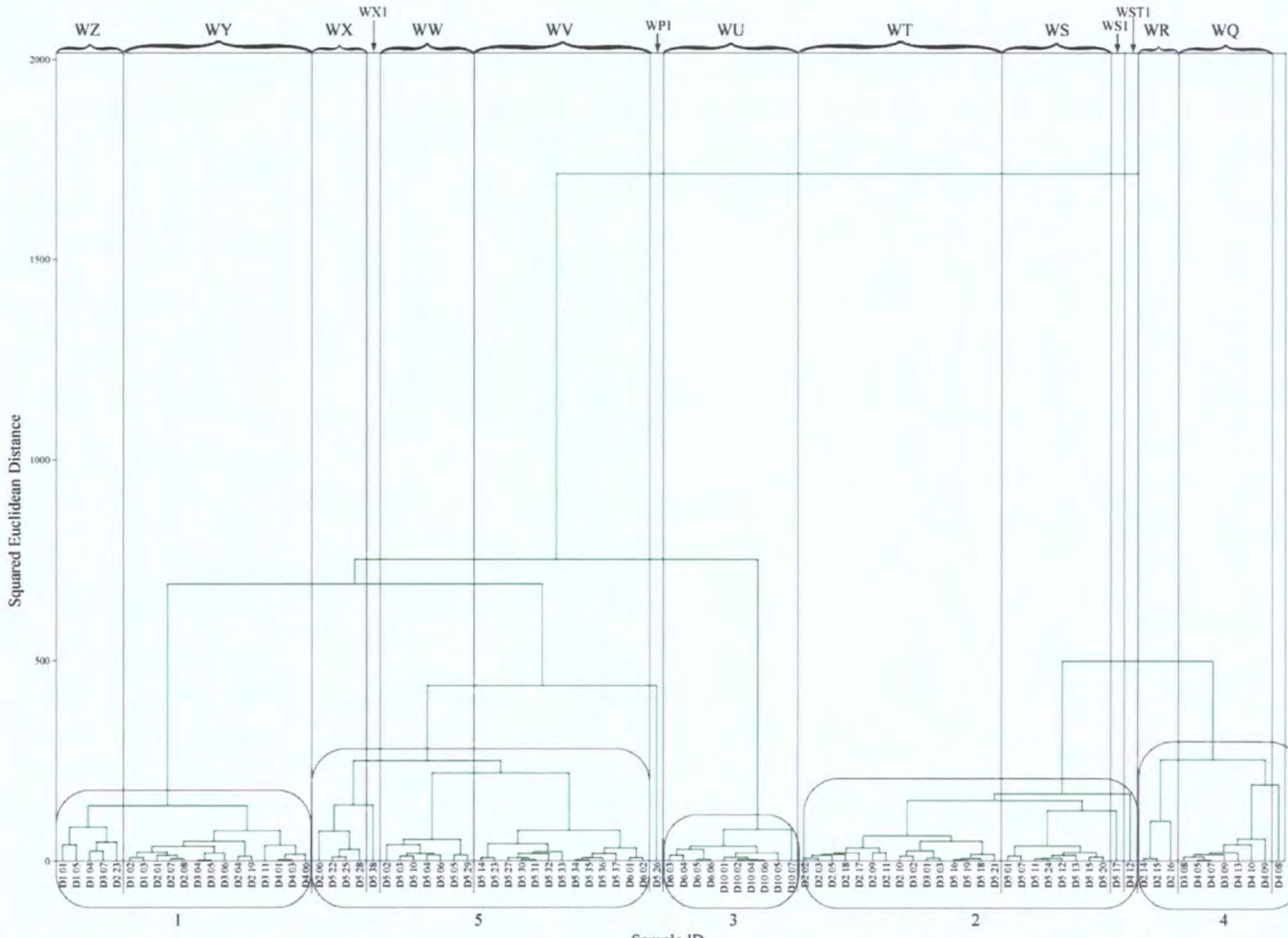


Figure 4.46. Dimlington diamicton, dendrogram of cluster analysis using Ward's method and combined z-scores, including geochemical groups (above) and five overall groups for comparison with other methods.

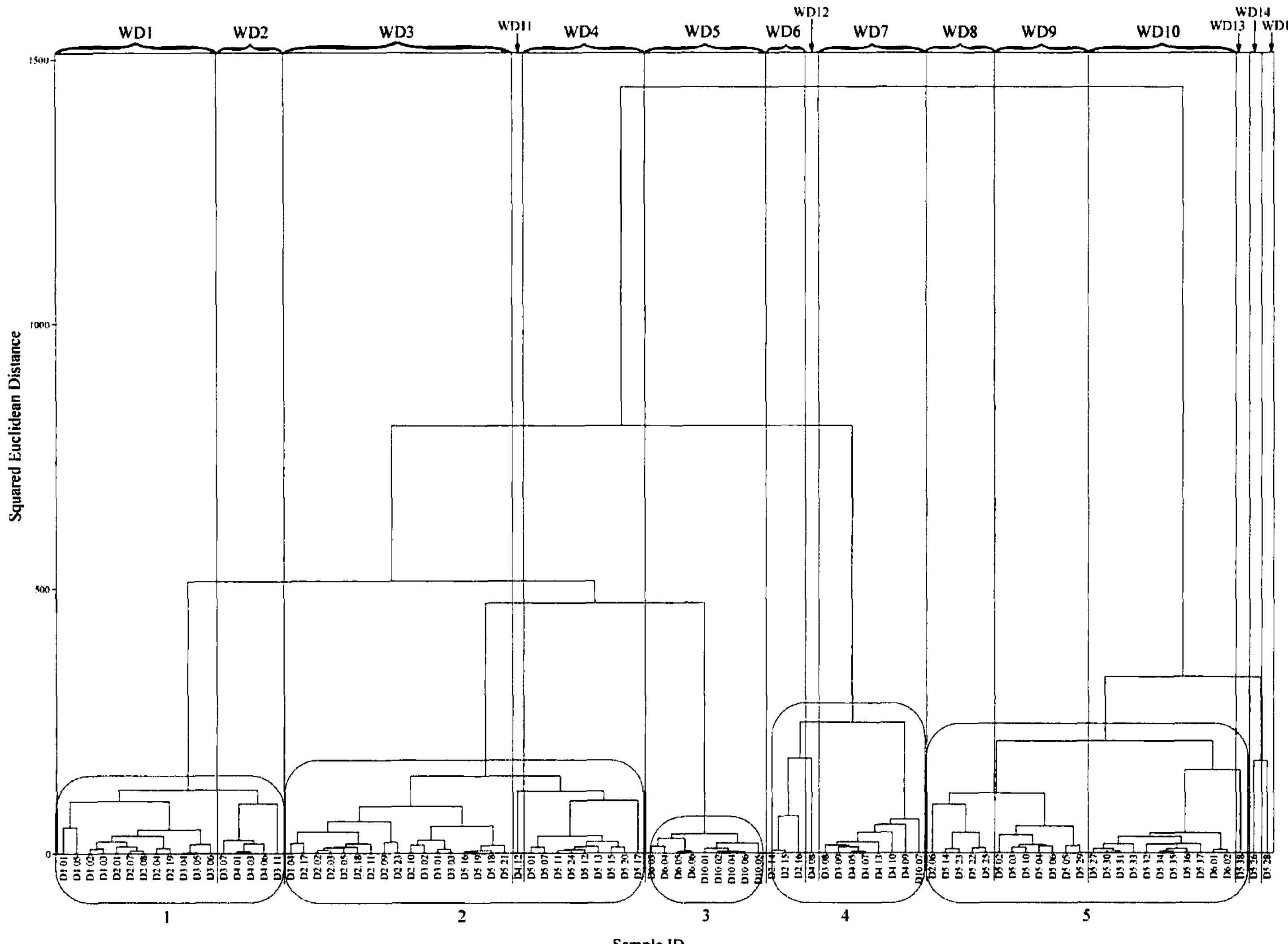


Figure 4.47. Dimlington diamicton, dendrogram of cluster analysis using Ward's method and individual z-scores, including geochemical groups (above) and five overall groups for comparison with other methods.

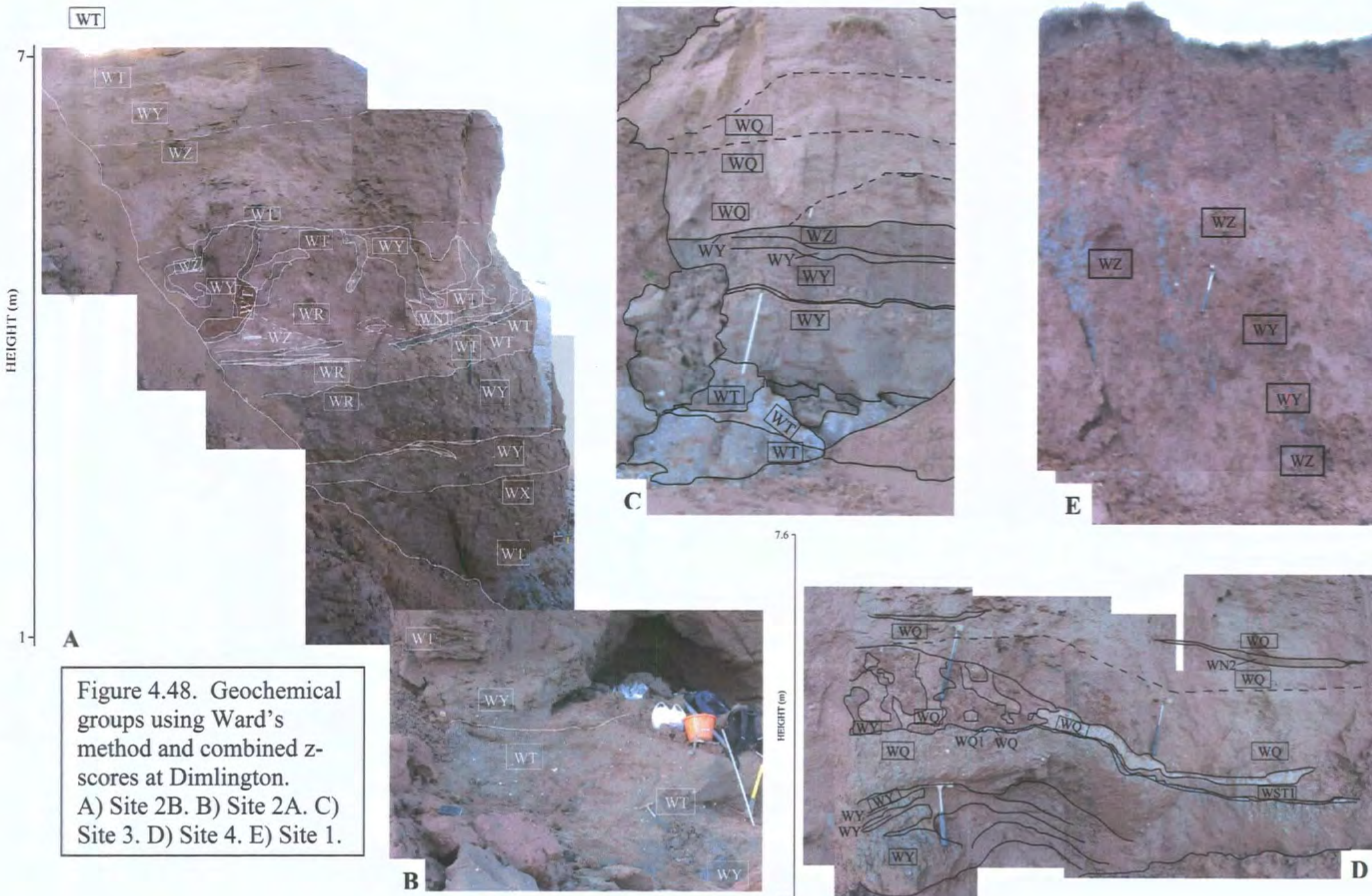


Figure 4.48. Geochemical groups using Ward's method and combined z-scores at Dimlington. A) Site 2B. B) Site 2A. C) Site 3. D) Site 4. E) Site 1.

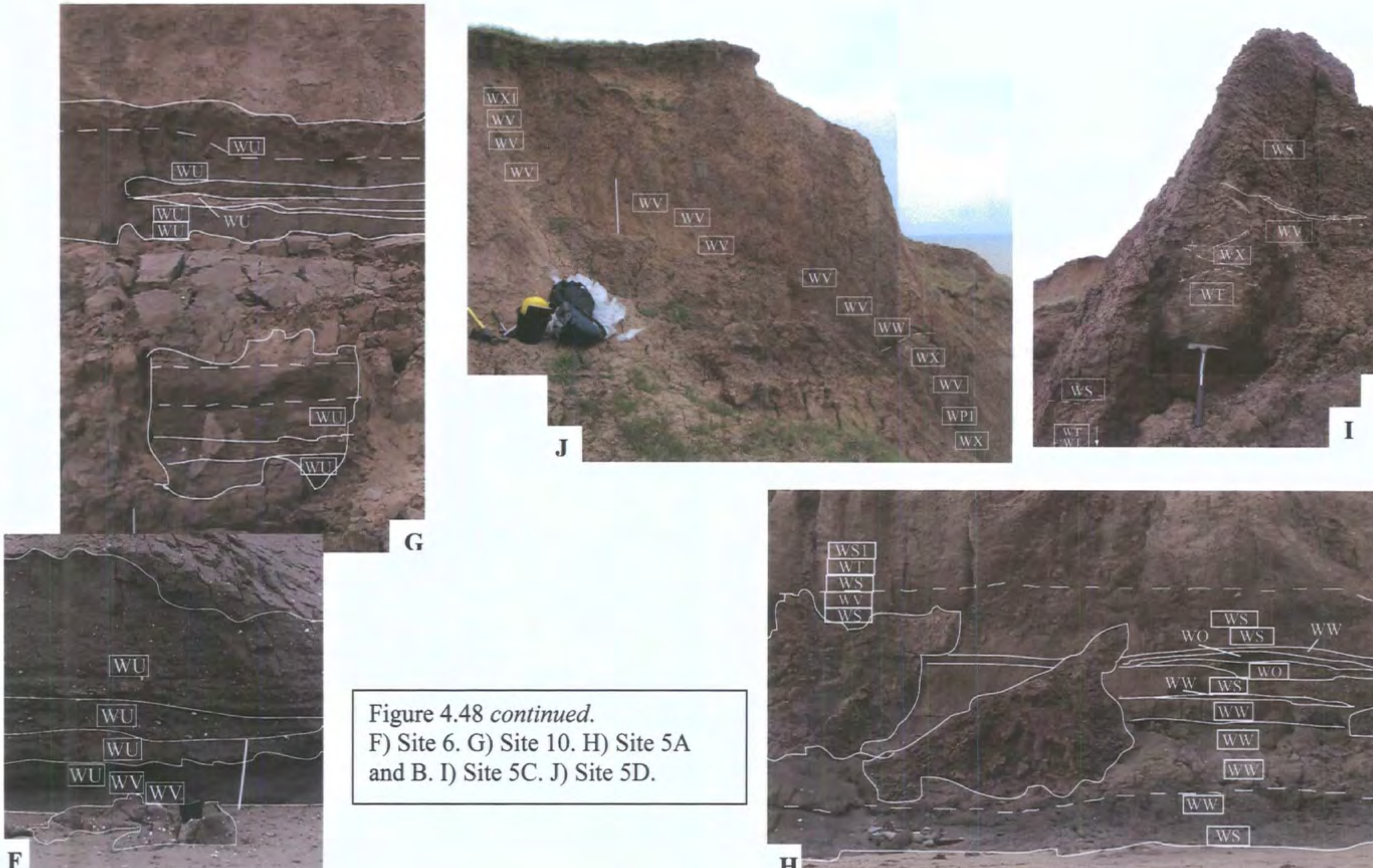


Figure 4.48 *continued.*
F) Site 6. G) Site 10. H) Site 5A and B. I) Site 5C. J) Site 5D.

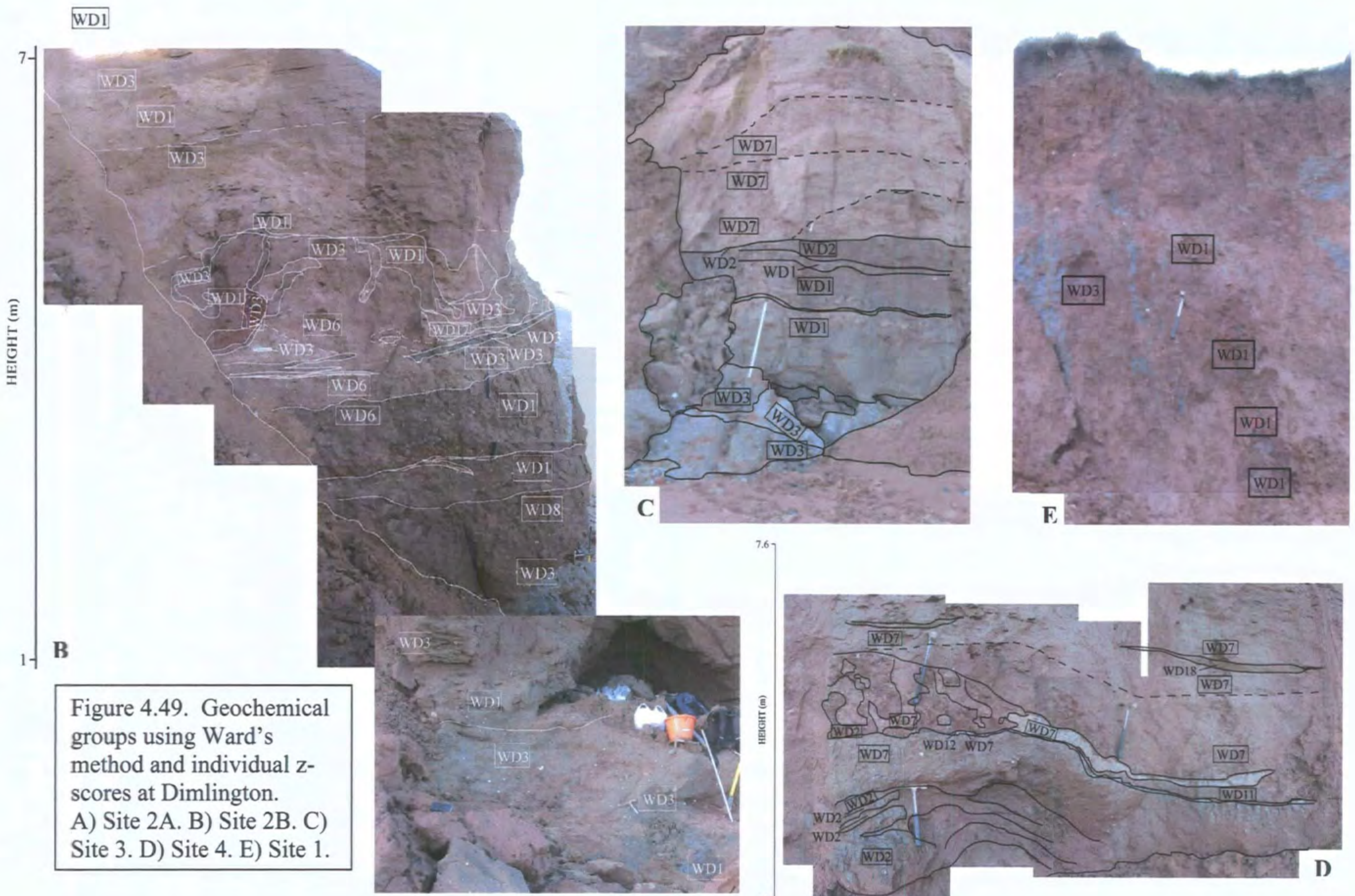


Figure 4.49. Geochemical groups using Ward's method and individual z-scores at Dimlington. A) Site 2A. B) Site 2B. C) Site 3. D) Site 4. E) Site 1.

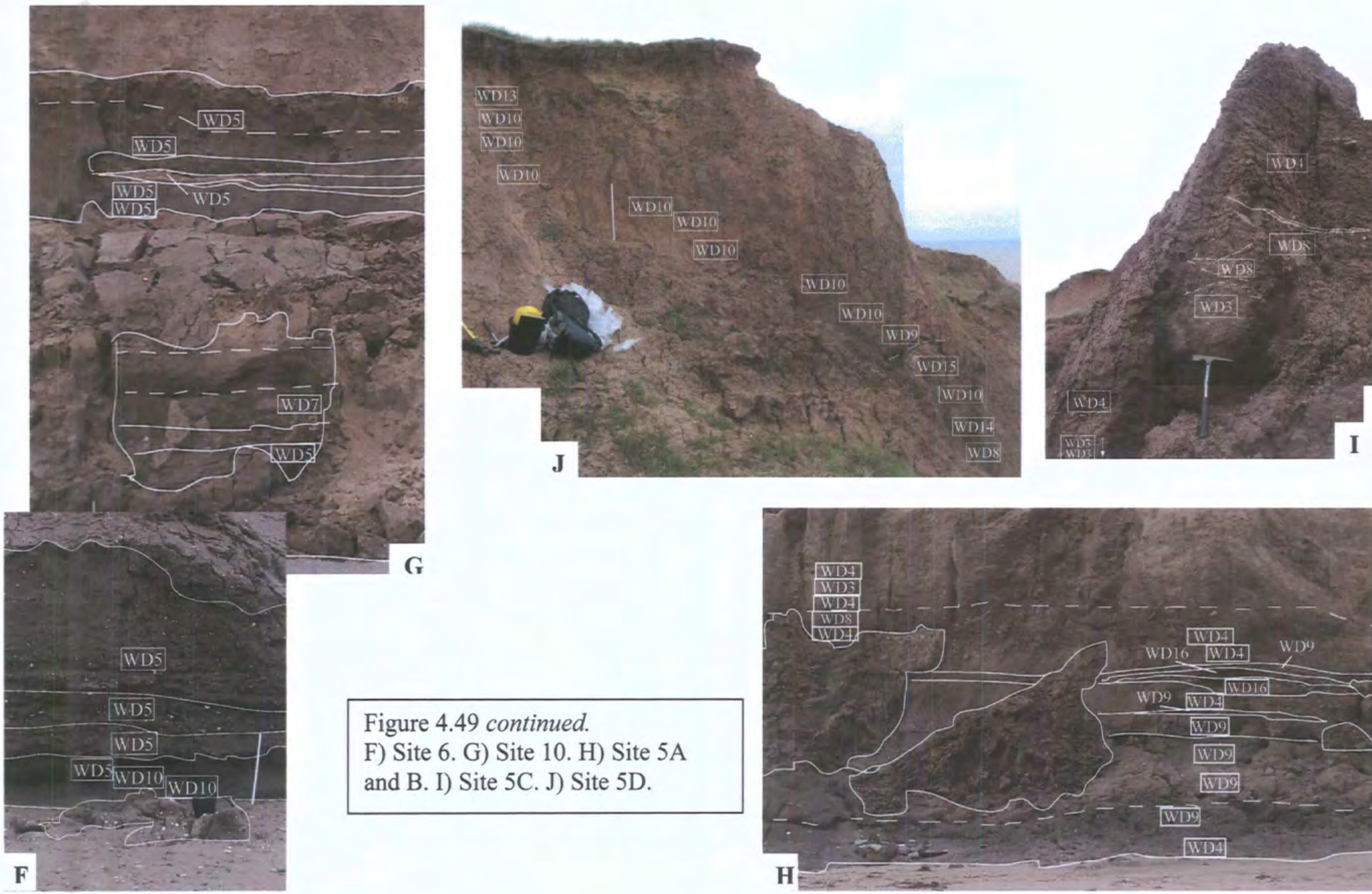


Figure 4.49 *continued.*
F) Site 6. G) Site 10. H) Site 5A and B. I) Site 5C. J) Site 5D.

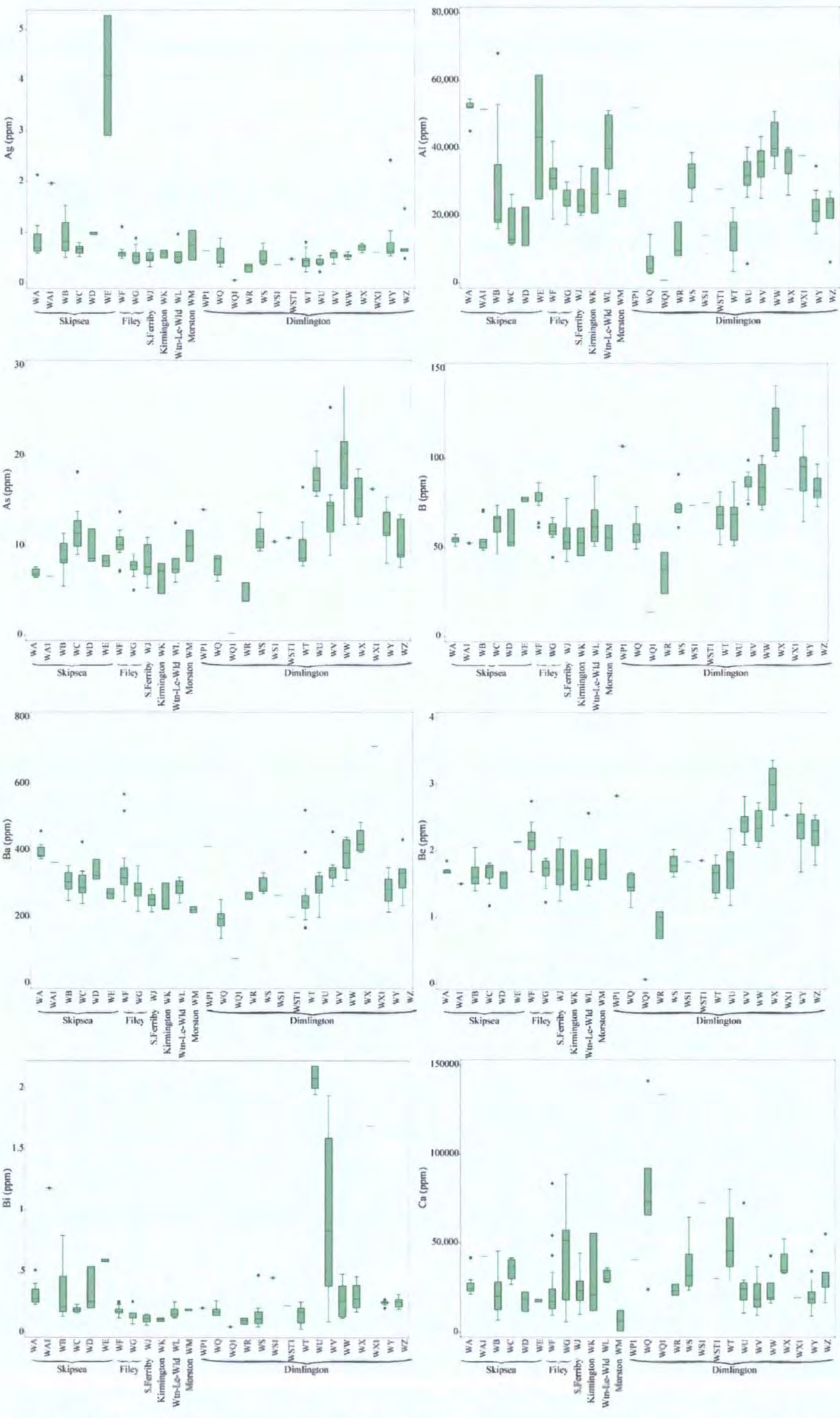


Figure 4.50. Element abundances within diamicton groups defined by Wards' method, combined z-score cluster analysis.

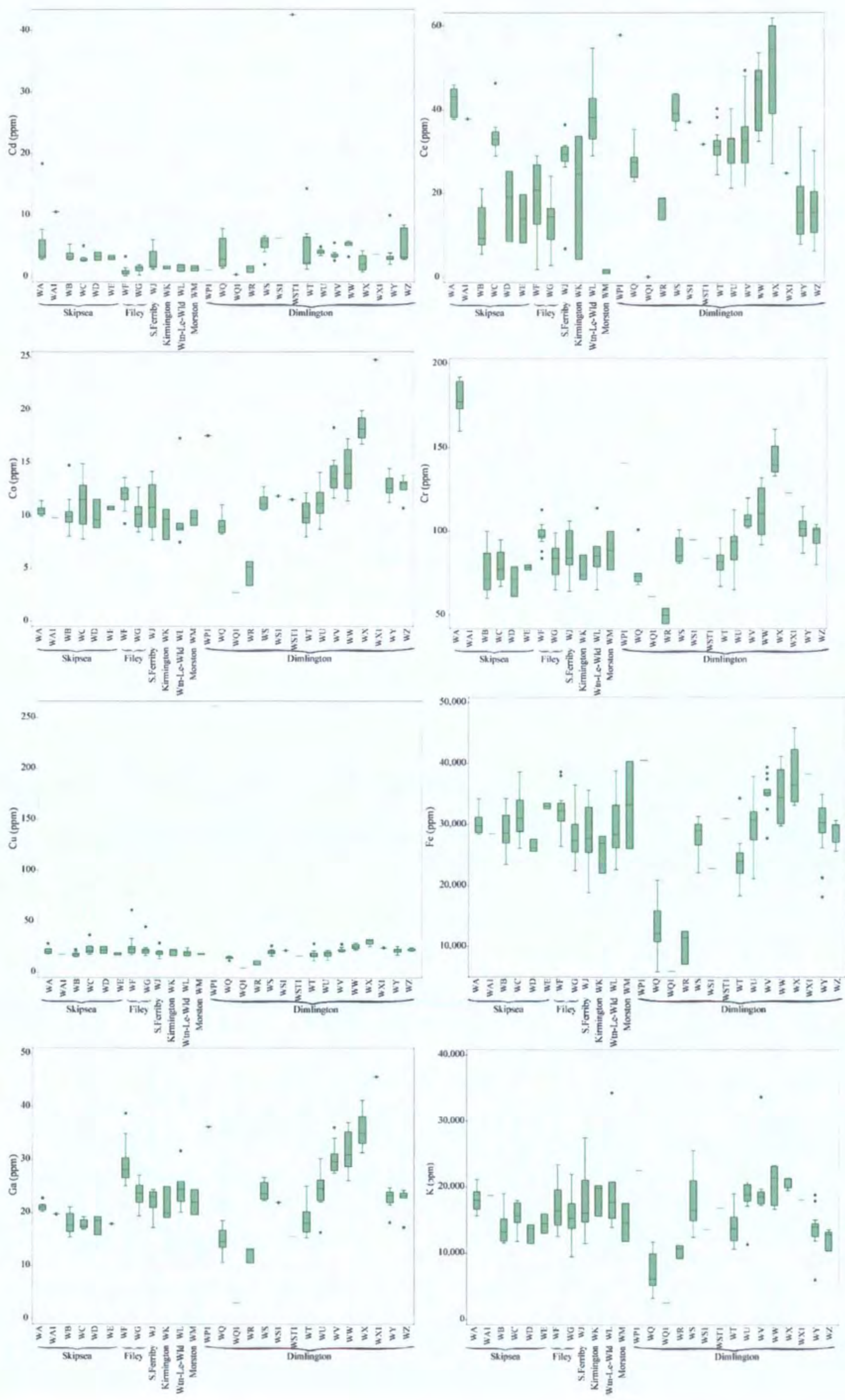


Figure 4.50 *continued.*

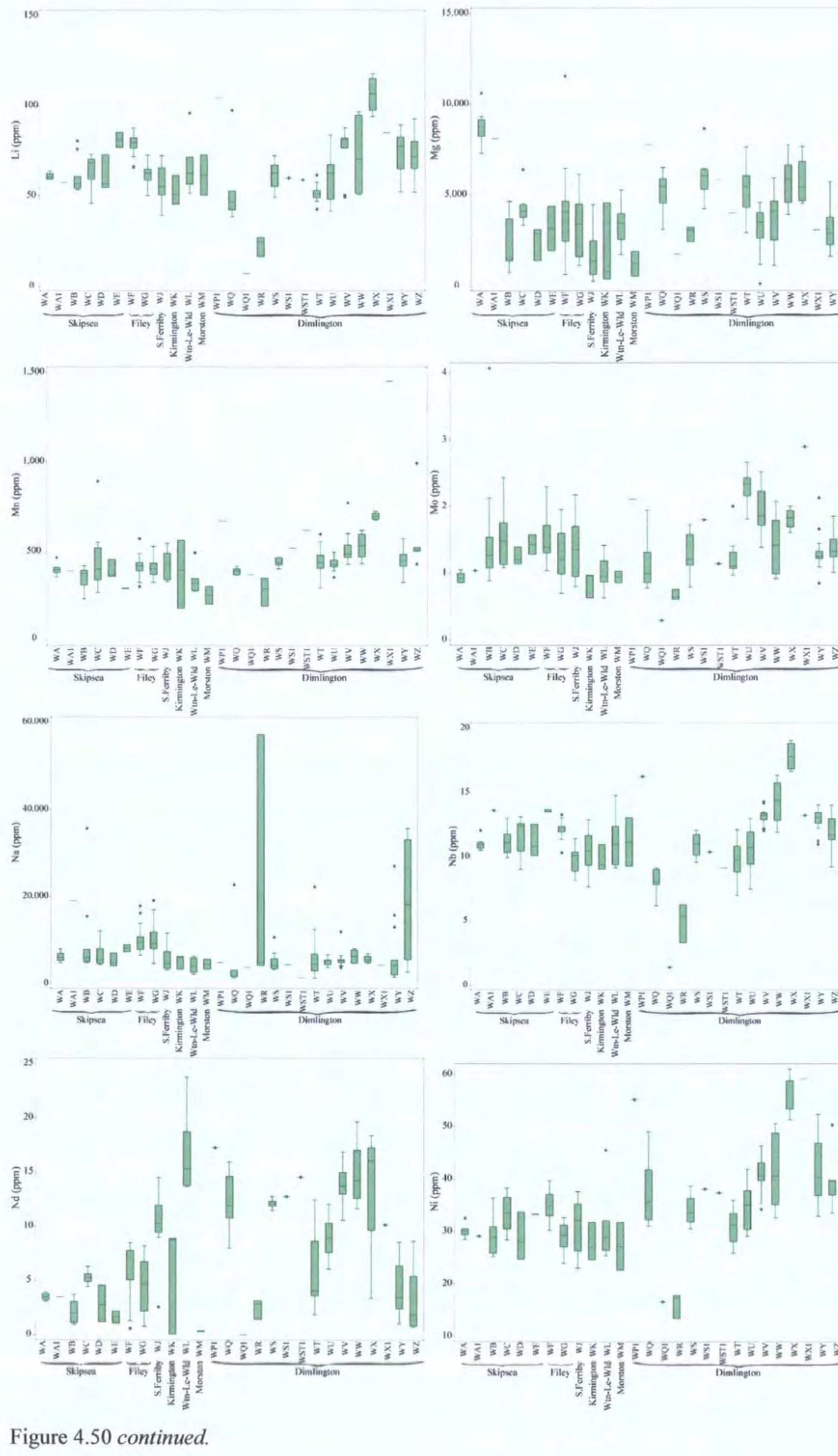


Figure 4.50 *continued.*

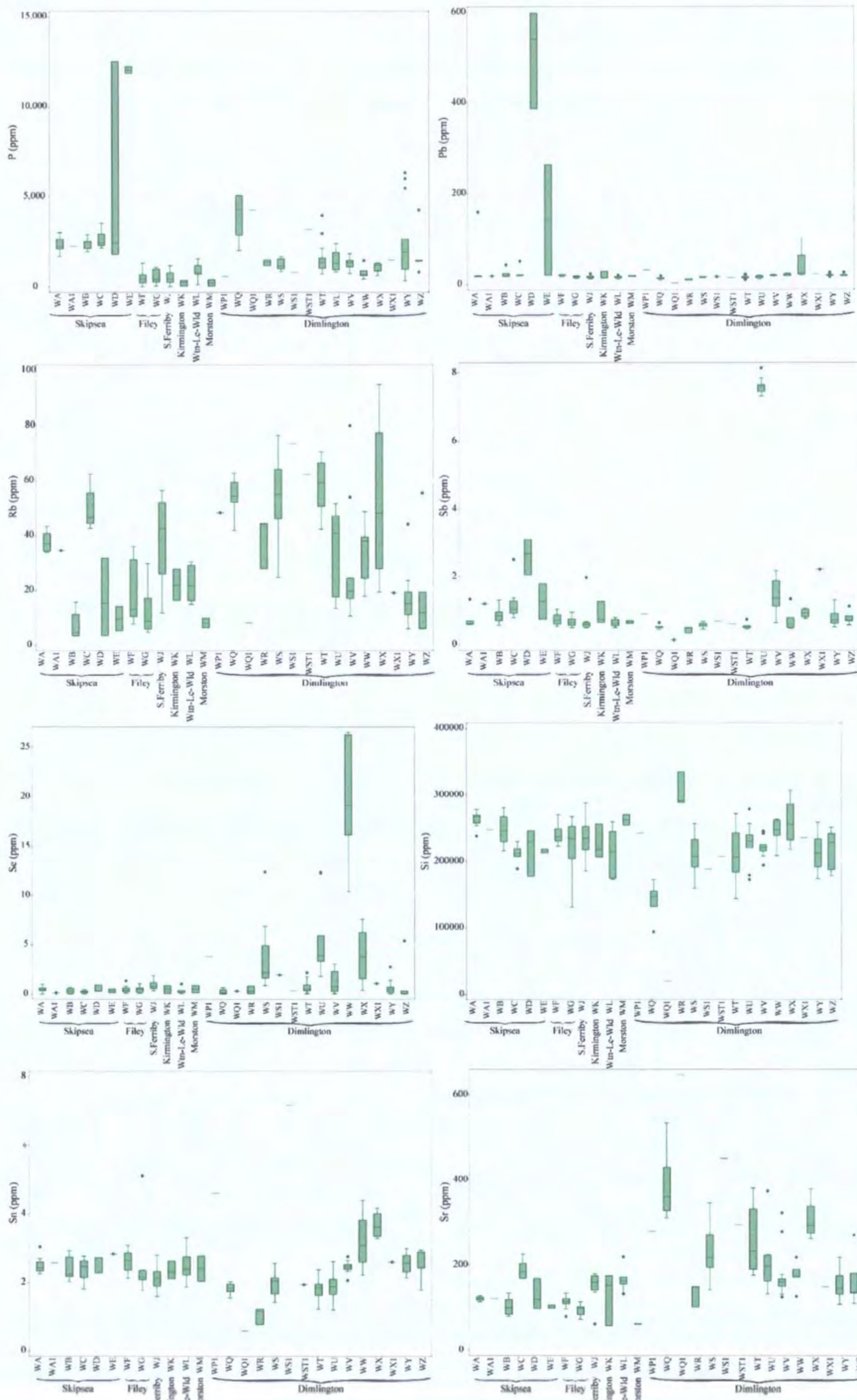


Figure 4.50 *continued.*

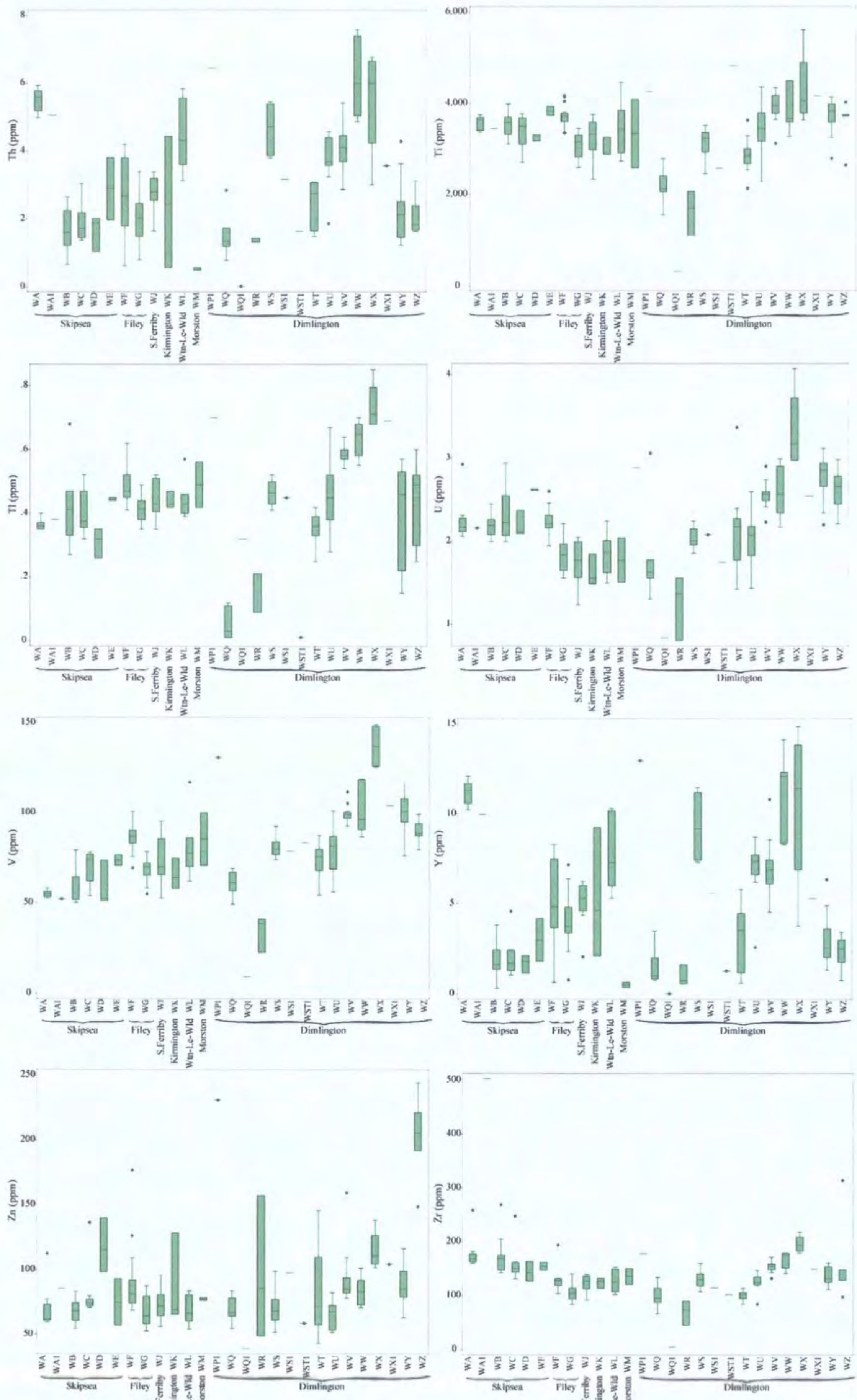


Figure 4.50 *continued.*

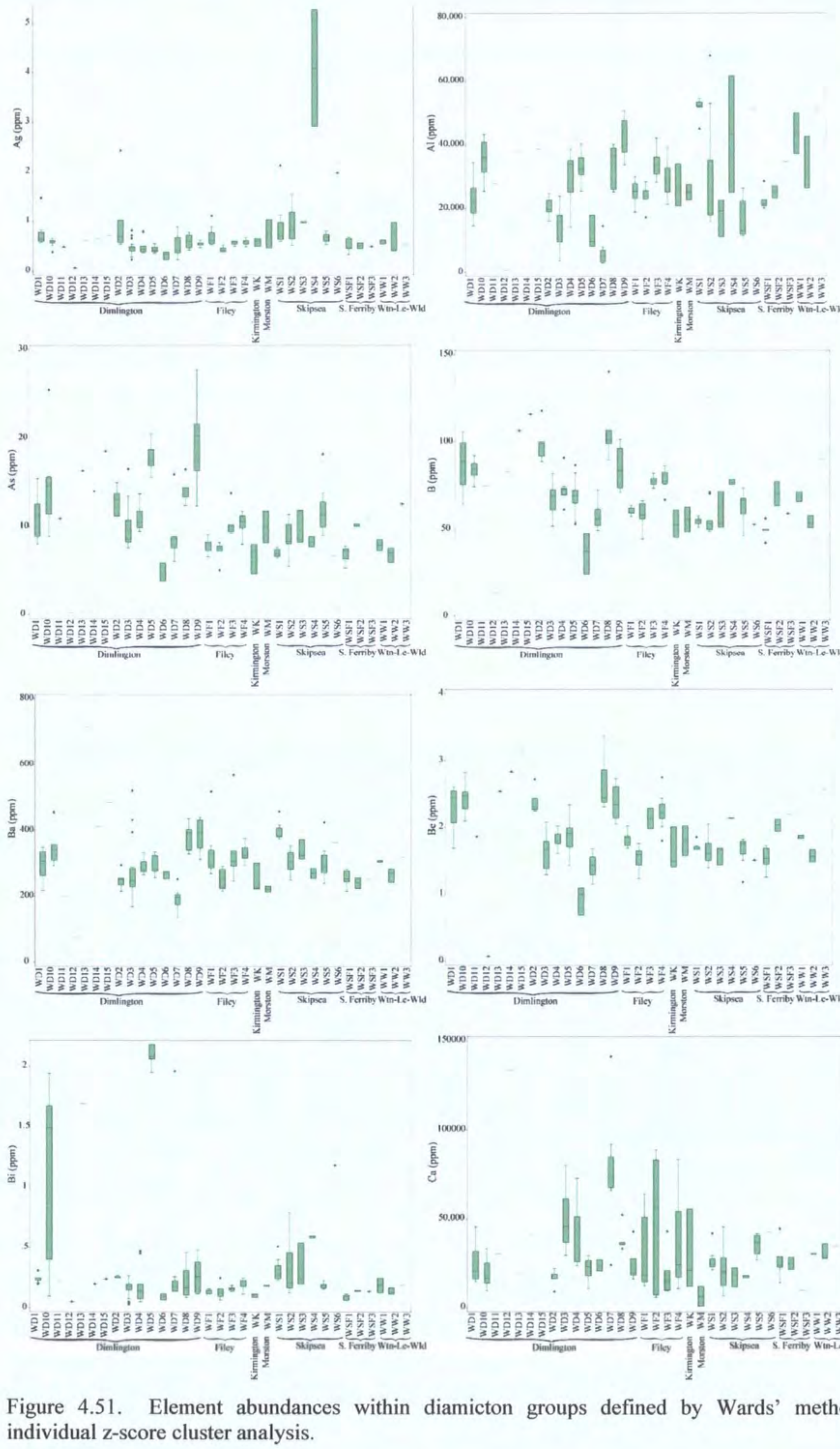


Figure 4.51. Element abundances within diamicton groups defined by Wards' method, individual z-score cluster analysis.

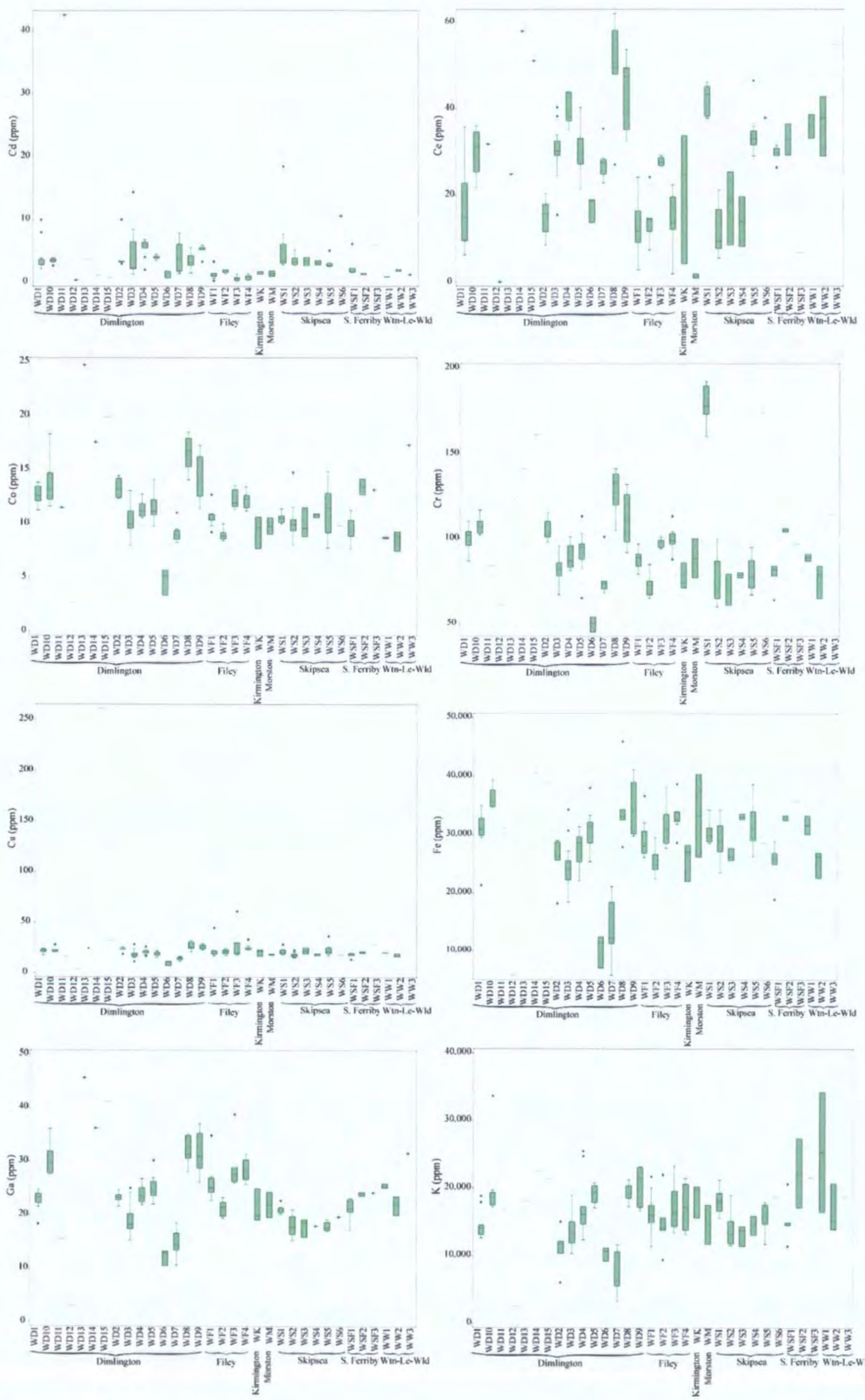


Figure 4.51 *continued.*

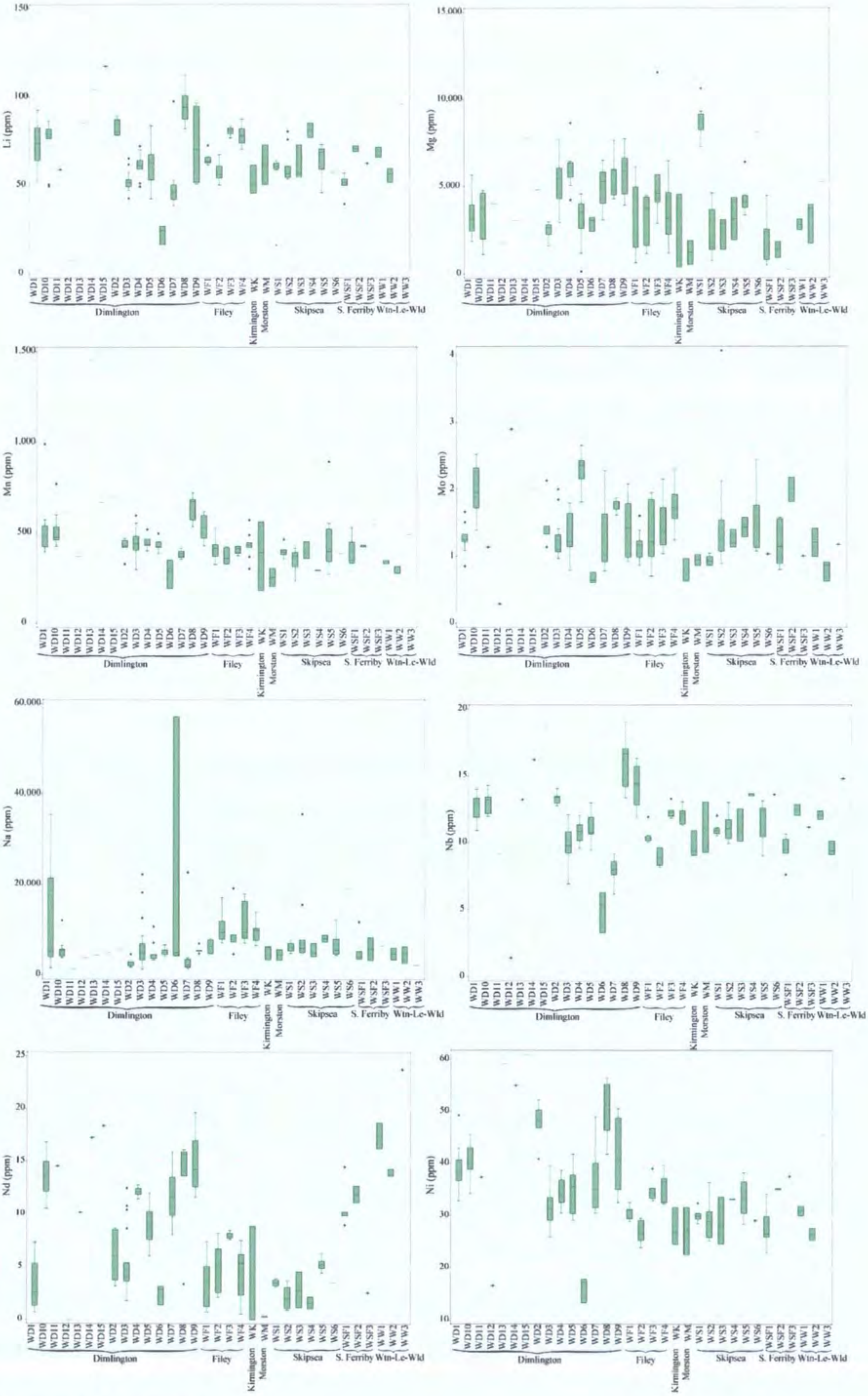


Figure 4.51 *continued.*

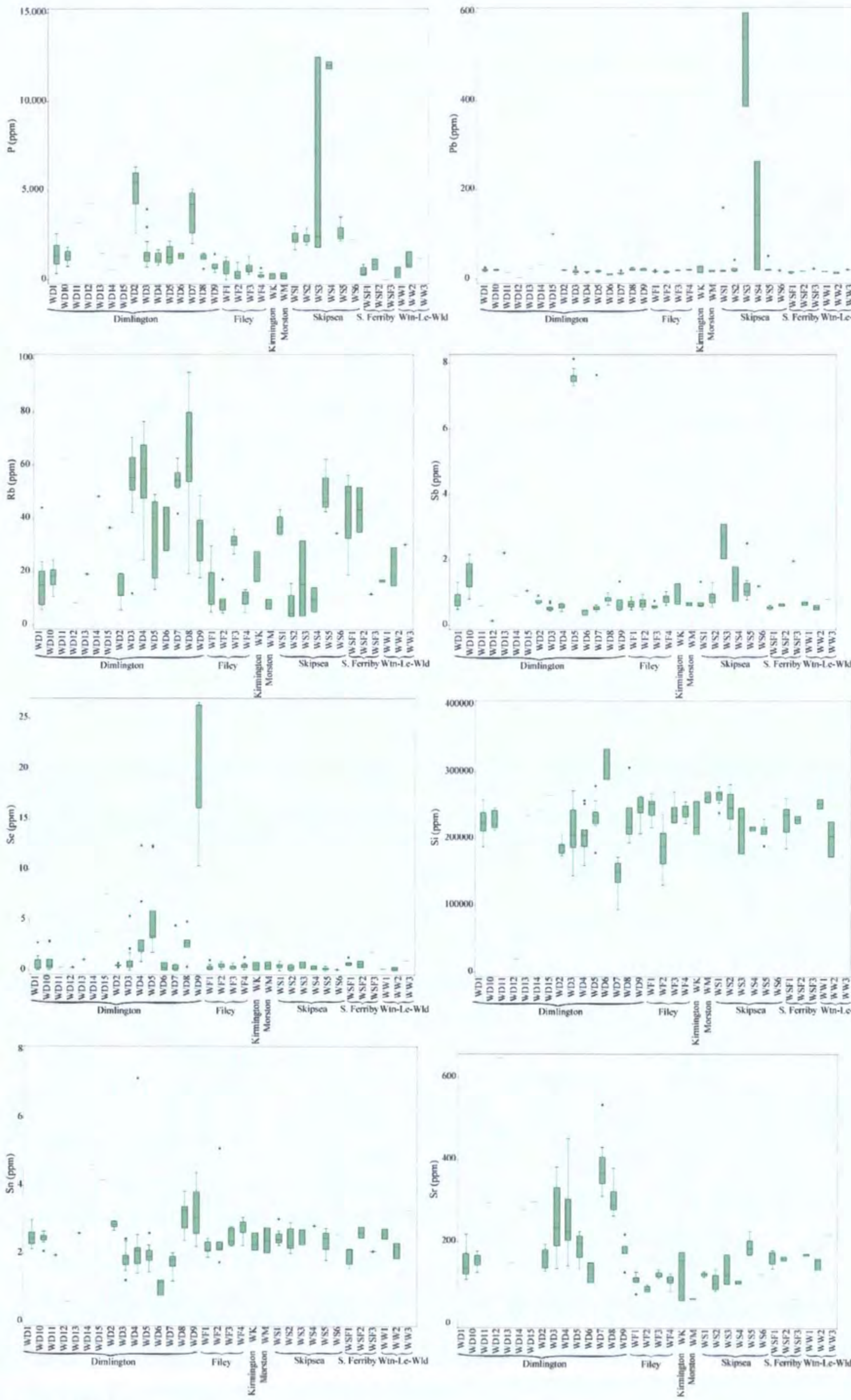


Figure 4.51 *continued.*

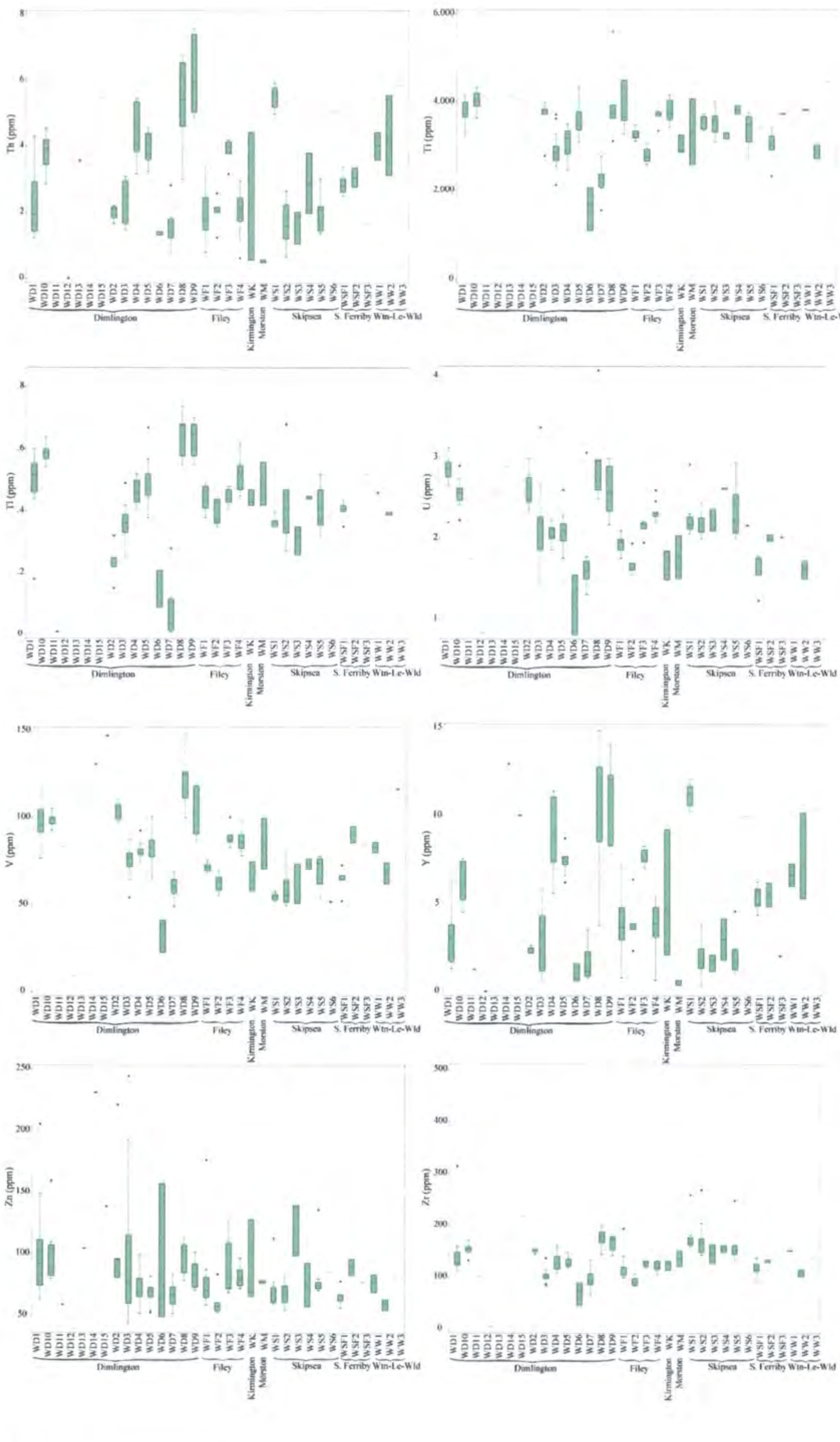


Figure 4.51 *continued.*

Dimlington Sands, Clays and Gravels

Gravels, sands and clays found above the diamicton at Dimlington Site 2 cluster closely with diamicton samples at this site, demonstrating similar suites of elements between the different sediment types (see Appendix iii). Only one gravel sample displays a much higher dissimilarity, and is labelled as group CP/CD12/WN1/WD17 using the four cluster methods. There is also no pattern as to which type of sediment falls into which group at this site, where, using the complete linkage combined z-score groups as an example, the laminated clay, laminated sand and gravel samples all cluster closely with both samples from groups CZ and CW.

At Site 3, the laminated clay sample (D3.10) taken from above the light brown diamicton clusters strongly with the samples from this diamicton, and so is assigned to groups CW/CD4/WQ/WD7. The three laminated clay samples from Site 4 also fall into these groups due to showing a strong affinity with the light brown chalky diamictons at this site. Sandy-clay samples, taken from between the diamicton laminations at the base of Site 4 (Facies 2), cluster closely with this diamicton, and are therefore allocated to groups CZ/CD1/WY/WD2. The sample taken from the sand lens towards the top of the section at Site 4 shows limited similarity with any diamicton samples and is therefore labelled CR/CD4/WN2/WD18.

Samples taken from the gravel and clay units (D5.8 and D5.9) towards the base of the section at Site 5, cluster relatively closely with each other, but do not cluster closely to any of the diamictons at Site 5 (Facies 5, 6, 7), and are therefore assigned to groups CQ/CD2/WO/WD16. Cluster analysis on samples from Site 10 shows that the laminated clay sample (D10.3) displays a high similarity with the diamicton surrounding it, and is consequently allocated to groups CV/CD2/WU/WD5.

4.3.2 Skipsea

Complete Linkage

From analysis using combined z-scores, and the same similarity level as Dimlington (Euclidean distance 10), three groups are established at Skipsea (CA-CC) and one outlying sample (CD) (Figures 4.52 & 4.54). Group CA consists of the majority of samples from Sites 1 and 2 (Facies 1 and 2), and samples from the upper unit of Site 3 (Facies 3). Group CB includes the remaining samples from Site 1 (Facies 2), which were mainly in the upper half of the section, samples from the lower diamicton unit at Site 3 (Facies 1), and samples from above and below the sand cavity at Site 4 (Facies 1 and 5). Group CC contains the two samples taken from the diamicton bands within the sand cavity, and group CD represents sample S1.1 which clusters with group CA and CB following their amalgamation at a Euclidean distance of 13. Figure 4.44 shows that group CA is distinguished from the other Skipsea groups by a greater abundance of K, Mg, Rb, Cr, and Ce, whilst group CC contains much higher proportions of Ag than any other group at Skipsea or in the study as a whole (Figure 4.44).

Cluster analysis using individual z-scores produced four groups (CS1-CS4) at a Euclidean distance of 9 or less (Figures 4.53 & 4.55). CS1 contains samples from the lower unit of Site 1 (Facies 1), and includes sample S1.1. All of these samples, except S1.1 fall into the combined z-score group CA. CS2 contains some samples from the upper unit at Site 1 (Facies 2), all of the samples taken from below the clast band at Site 3 (Facies 1), and the samples from the upper and lower diamicton units at Site 4 (Facies 1 and 5). Most of these samples occur in the combined z-score group CB. CS3 contains the remainder of samples found in group CA and a few from group CB, from the upper till units at Sites 1, 2 and 3. Group CS4 is equivalent to the combined z-score group CC which contains two samples from diamicton bands within the sand cavity at Site 4 (Facies 4). In these groupings, CS1 contains similar element abundances to those in CA (Figures 4.44 & 4.45). Here, the abundance of Mg in CS1 is significantly greater than any of the other groups. The inter-quartile range is much smaller than that of group CA, indicating that samples in the combined z-score group CA which were placed into group CS3 by the individual z-scores method, had lower abundances of Mg. CS1 is also distinguished from CS3 by a much higher abundance of Cr, Y, Ce and Th, which may have also caused the division of the combined z-score group CA (Figure 4.45).

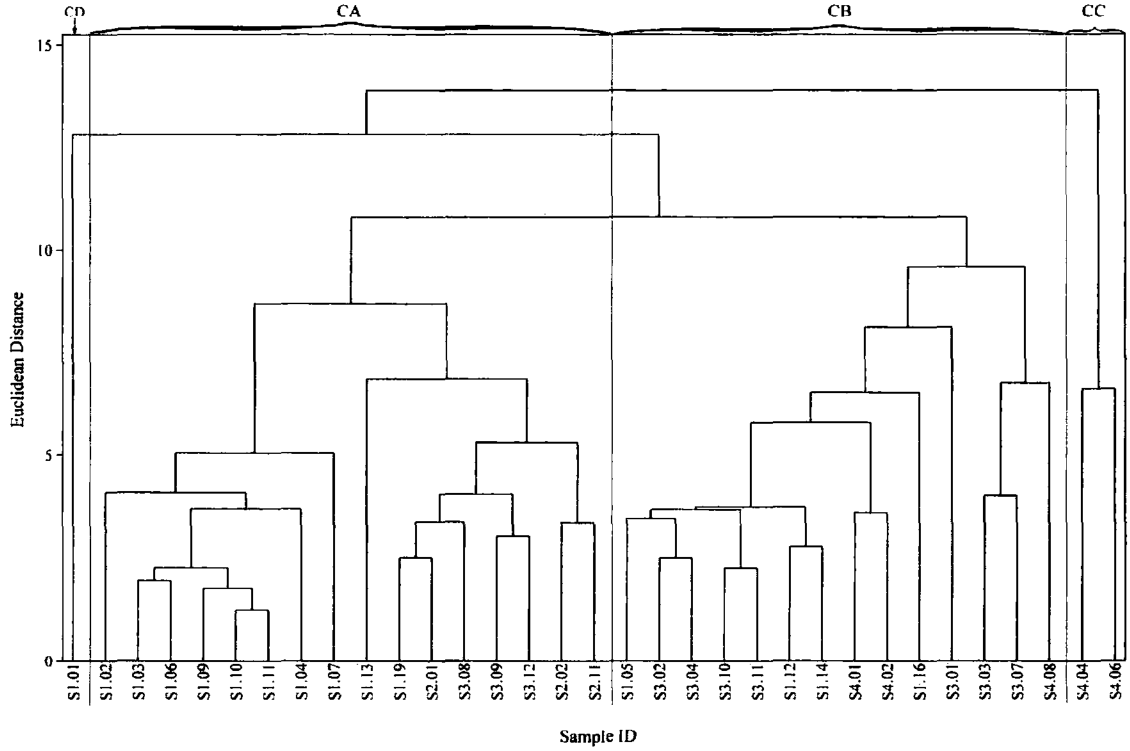


Figure 4.52. Skipsea diamicton, dendrogram of cluster analysis using complete linkage and combined z-scores.

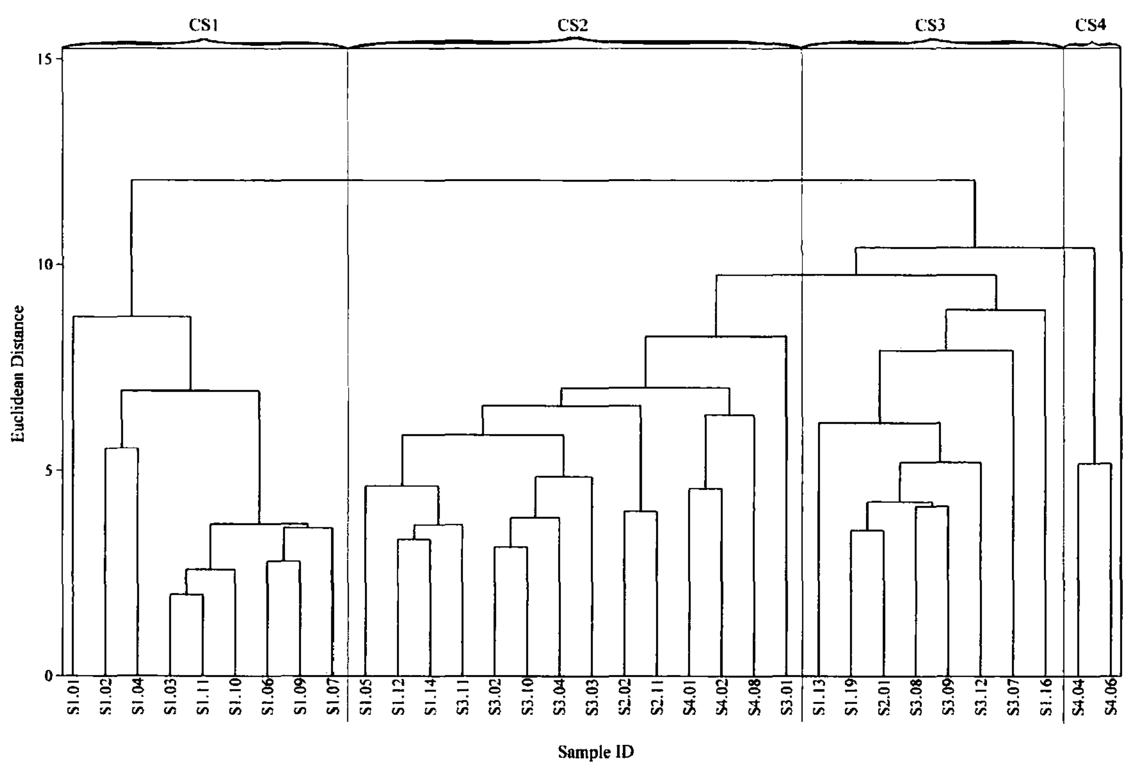
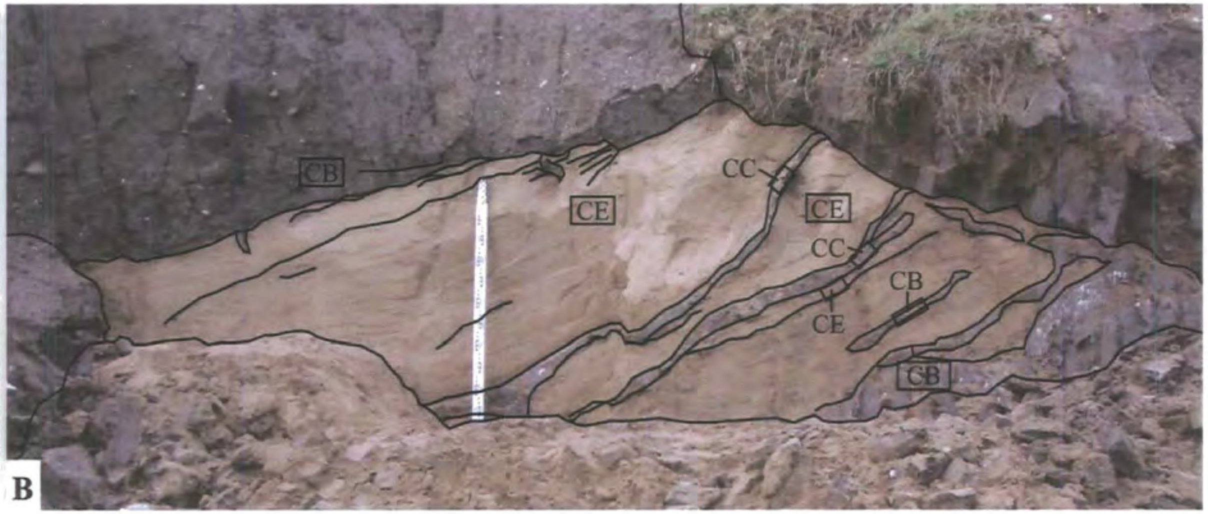


Figure 4.53. Skipsea diamicton, dendrogram of cluster analysis using complete linkage and individual z-scores.



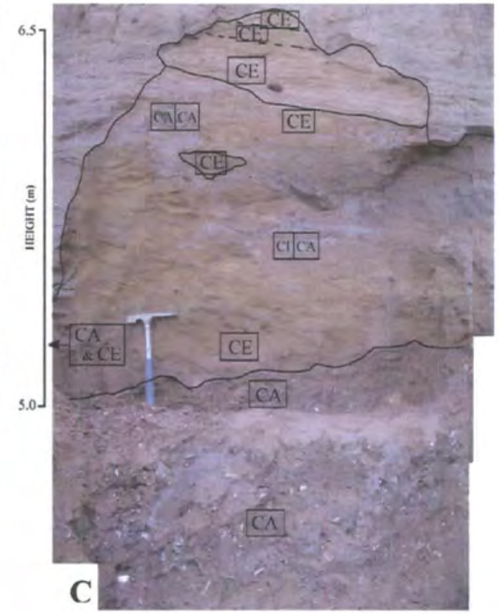
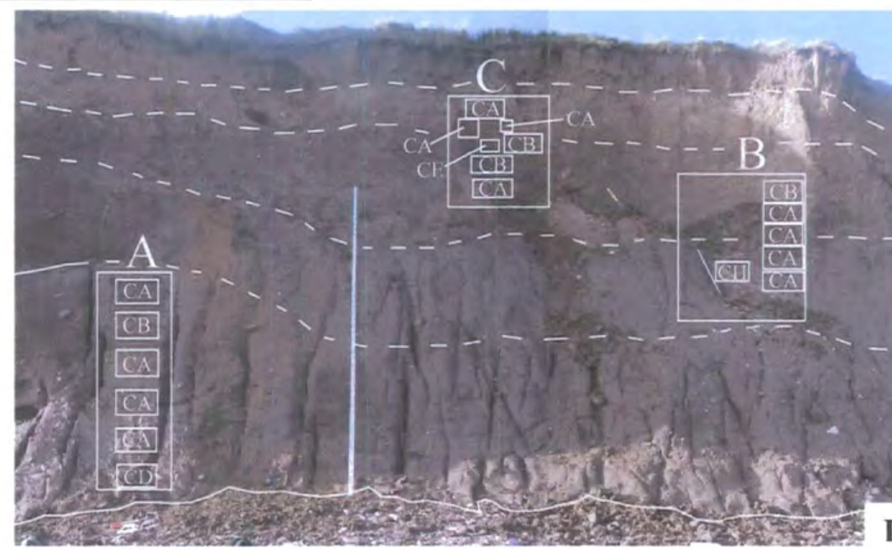
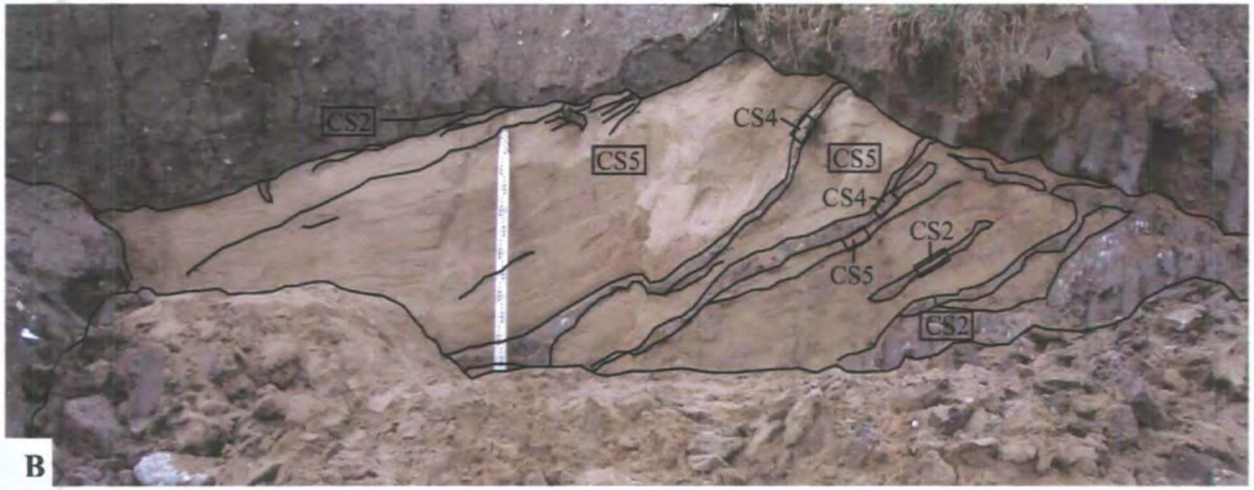


Figure 4.54. Geochemical groups using complete linkage and combined z-scores at Skipsea. A) Site 3. B) Site 4. C) Site 2. D) Site 1.





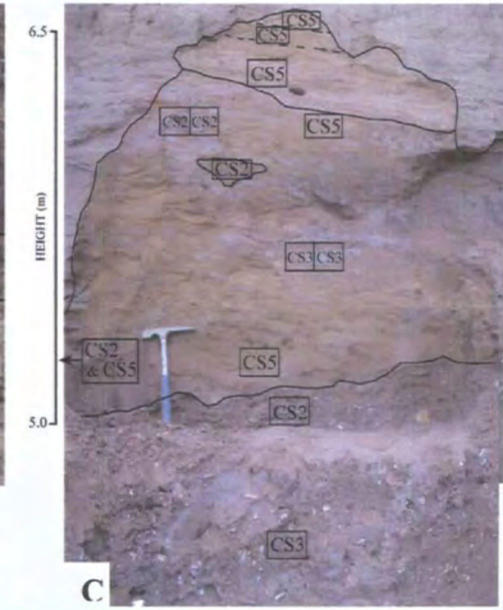
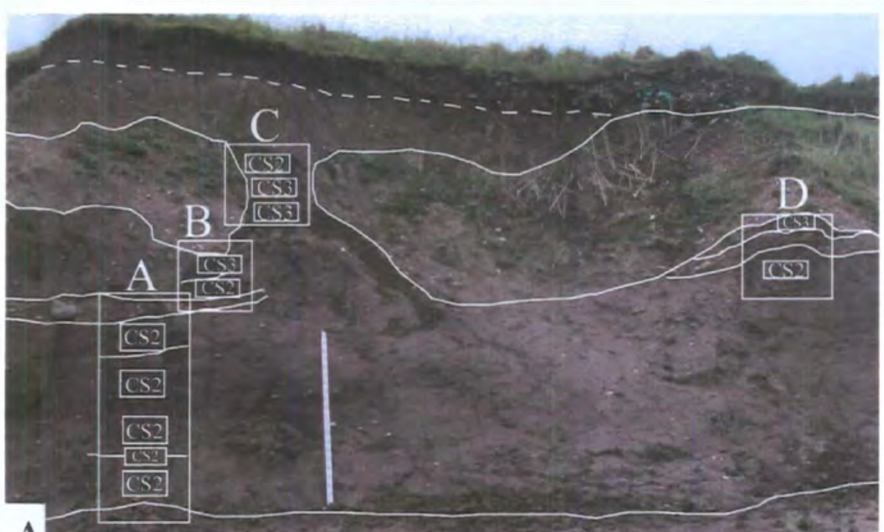


Figure 4.55. Geochemical groups using complete linkage and individual z-scores at Skipsea. A) Site 3. B) Site 4. C) Site 2. D) Site 1.



Ward's Method

Combined z-scores used in Ward's method created five groups at a squared Euclidean distance of 100 or less, labelled WA-WE, with one outlier, sample S1.1 named WA1. Group WA contains samples from the lower diamicton at Site 1 (Facies 1) (Figures 4.56 & 4.58). Samples within this group are almost identical to those in the complete linkage group CS1, although how these samples cluster together is slightly different. Samples in group WB, which contain a fairly similar assemblage of samples to that of CS2, originate from the upper diamicton at Site 1 (Facies 2), and the lower diamictons at Sites 3 and 4 (Facies 1). Group WC is fairly similar to that of CS3 and includes samples from the upper diamictons at Sites 1, 2 and 3 (Facies 2 and 3). Group CD contains three samples, S3.3 (Facies 1), S3.7 (Facies 3), which occur below and above the band of clasts at Site 3, and S4.8, which was taken from diamicton (Facies 5) above the sand cavity at Site 4. This clustering also occurs using combined z-scores in the complete linkage group CB, but the dissimilarity of this cluster with others was not high enough to place it in a separate group. Group WE contains the two diamicton bands (Facies 4) at Site 4, and corresponds to groups CC and CS4 from the complete linkage method.

Individual z-score analysis also produced five groups named WS1-WS6 at a squared Euclidean distance of 100 or less. S1.1 again did not cluster with any groups at this similarity, and is labelled WS6 (Figures 4.57 & 4.59). Samples within each cluster group are identical to cluster groups formed using combined z-scores, where WS1 corresponds to WA, WS2 to WB, WS3 to WD, WS4 to WE and WS5 equates to WC. However, even though the groups remain the same, the way in which the groups cluster with each other changes, and the way in which samples cluster with one another within each group changes too.

Skipsea Overall

All four methods of cluster analysis produce fairly consistent groups. The clusters show that the lower diamicton at Site 1 (Facies 1) forms a distinct group which clusters with the other groups at the highest dissimilarity (Euclidean distance of 12 and a squared Euclidean Distance of between 450 and 600). This group is differentiated from the other groups at Skipsea by higher abundances of K, Mg, Rb, Cr and Ce (Figures 4.44,

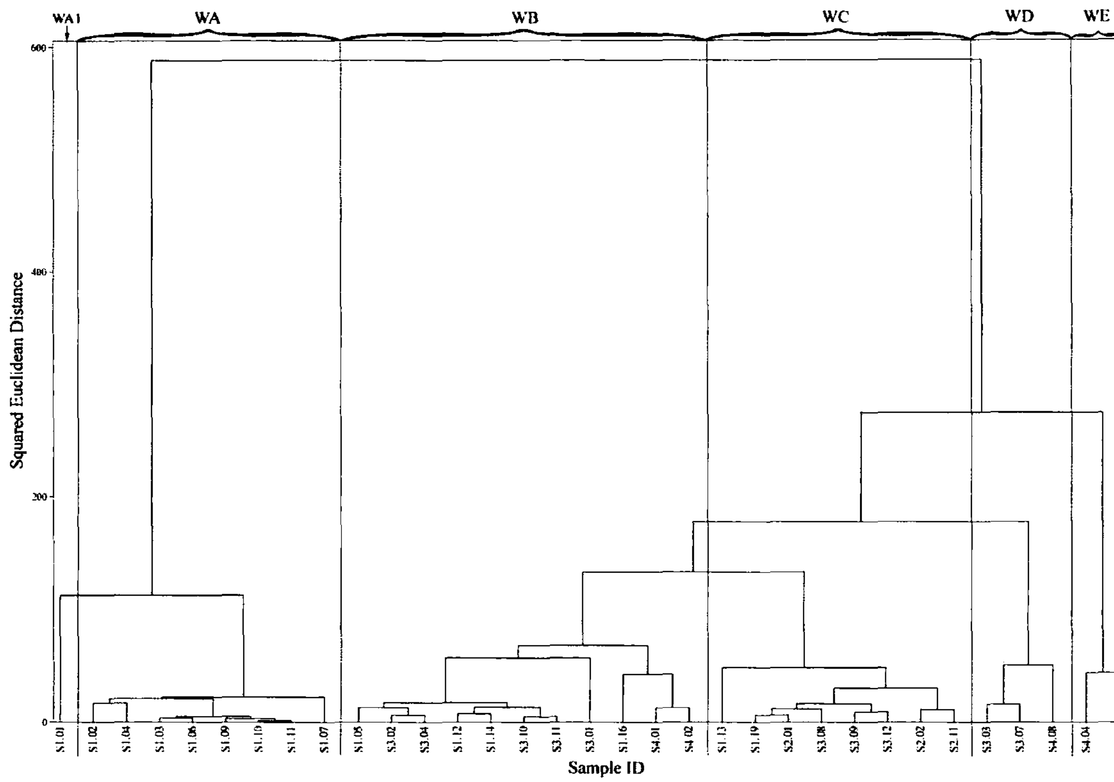


Figure 4.56. Skipsea diamicton, dendrogram of cluster analysis using Ward's method and combined z-scores.

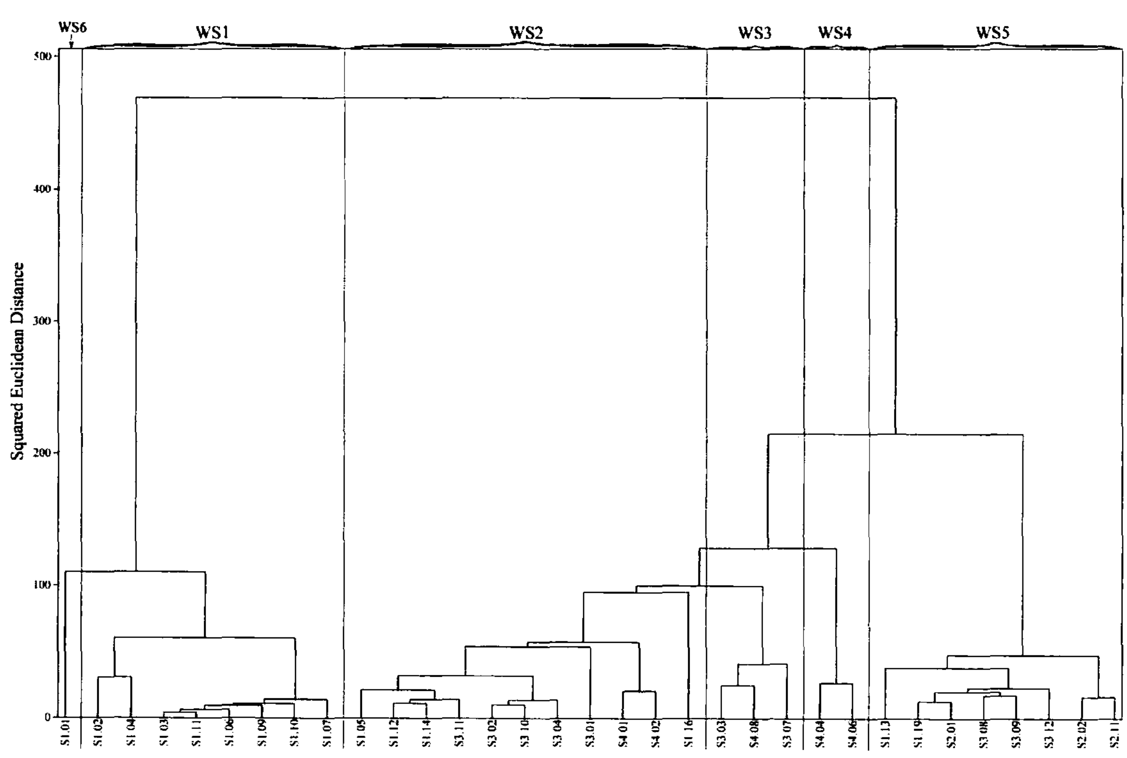


Figure 4.57. Skipsea diamicton, dendrogram of cluster analysis using Ward's method and individual z-scores.

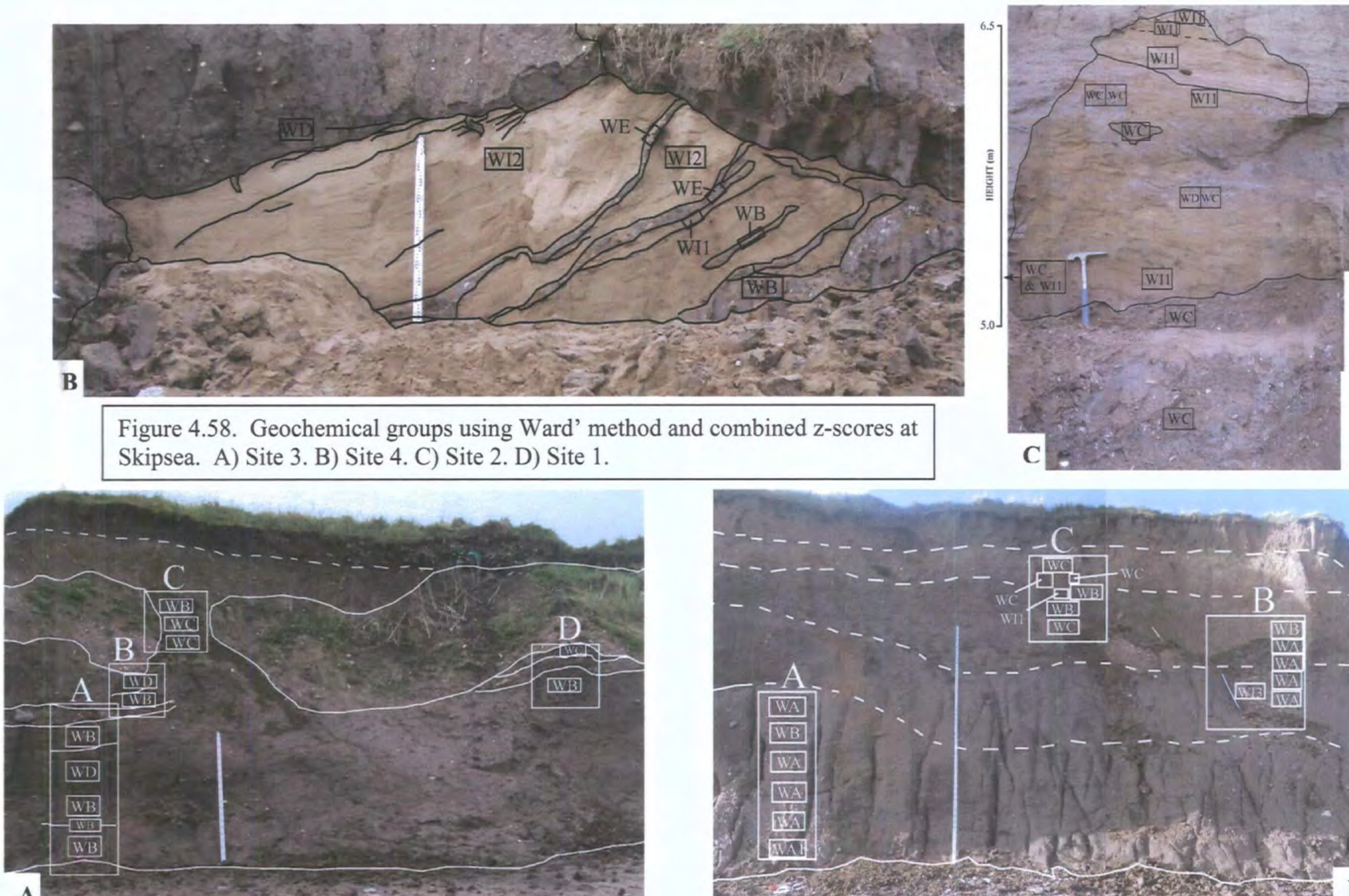


Figure 4.58. Geochemical groups using Ward' method and combined z-scores at Skipsea. A) Site 3. B) Site 4. C) Site 2. D) Site 1.

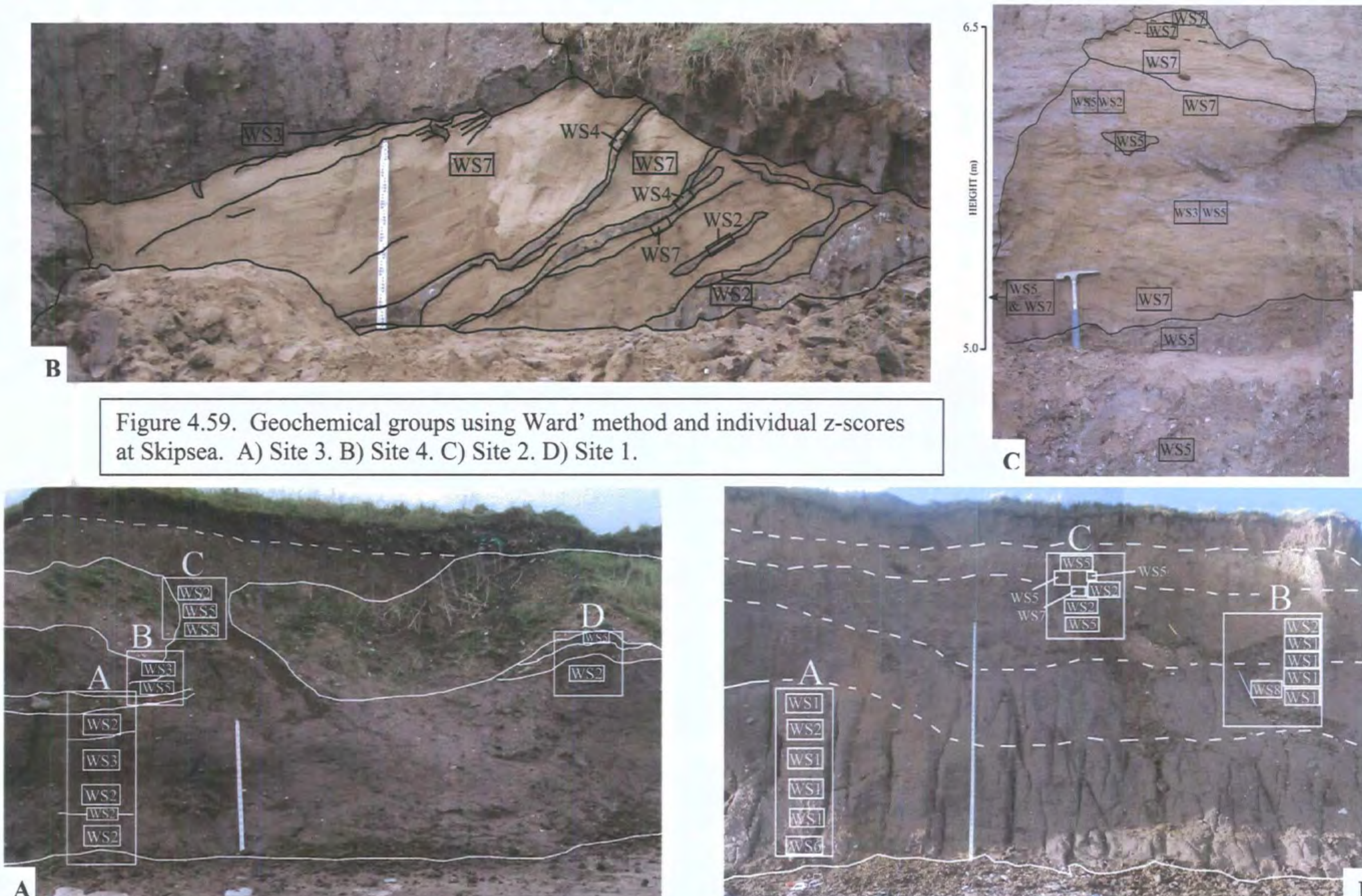


Figure 4.59. Geochemical groups using Ward' method and individual z-scores at Skipsea. A) Site 3. B) Site 4. C) Site 2. D) Site 1.

4.45, 4.50 & 4.51). Cluster analysis also divides the geochemistry of the samples at Site 3 into a group from the diamicton below the band of clasts (Facies 1), and a group from the diamicton above the clast band (Facies 3). The only exception is sample S3.10, which clusters with those diamictons below the clast band. This could be due to changes in the geochemistry of the diamicton matrix due to weathering at the top of the section. Samples from the upper diamicton at Sites 1 and 2 (Facies 2) cluster with diamicton samples from both above and below the clast band at Site 3 (Facies 1 and 3), indicating inhomogeneity within this upper unit, again possibly due to weathering, or indicating that the diamictons at Site 3 are geochemically similar. The diamictons above and below the sand cavity at Site 4 (Facies 1 and 5) cluster with the lower diamicton unit at Site 3 (Facies 1), whilst the diamicton bands (Facies 4) within the sand hollow form a separate group which is significantly geochemically different from the other groups, containing much greater abundances of P, Li and Ag (Figures 4.44, 4.45, 4.50 & 4.51).

Skipsea Sands, Clays and Gravels

Samples taken from sand units at Skipsea form an entirely separate group and cluster after the amalgamation of all the other samples (see Appendix iii). This group is labelled CE and CS5 for the complete linkage results using combined and individual z-scores, and WI and WS7 using Ward's method for combined and individual z-scores. The only exception to this grouping of sands is a sand lens found towards the top of the Site 1 section, which clusters with diamictons from groups CA, CS2, WC, WS5. Gravel and clay lenses, which also occur in the upper sections of Sites 1 and 2, also cluster with diamicton samples in the same section (Facies 2). Similarly, the sandy clay bands in the lower diamicton (Facies 1) at Site 3 predominantly cluster with this diamicton. S1.8 was taken from the clay fold at Site 1 and contains a unique geochemical signature compared to any of the other samples taken from Skipsea, clustering with the rest of the already grouped diamicton samples at a Euclidean distance of over 15 using the complete linkage method, and with samples from the upper diamictons at Sites 1 and 3 at a squared Euclidean distance of about 250, using Ward's method.

4.3.3 Filey Brigg

Complete Linkage

Following the same similarity level (Euclidean distance of 10) used to form cluster groups at Dimlington and Skipsea, the complete linkage analysis using combined z-scores groups all the samples from Filey into one group (Figures 4.60 & 4.62). This indicates that geochemical variation within the diamictons at Filey is much less than diamicton variation at Skipsea and Dimlington. All samples using combined z-scores are therefore categorised as group CF.

Euclidean distances are higher in the cluster dendrogram produced by the individual z-scores. This is because the z-scores are no longer influenced by the large number of samples at Dimlington and Skipsea. Four groups are formed at a Euclidean distance of 9, named CF1-CF4. Sample F1.1 does not cluster with groups CF1 and CF2 until a Euclidean distance of almost 13, and so is labelled CF5 (Figures 4.61 & 4.63). The four groups can be sub-divided into CF1 and CF2 which cluster at a Euclidean distance of 10, and CF3 and CF4 which cluster at a distance of 11.25. The two groups do not then cluster together until a Euclidean distance of 14.9. Group CF1 contains samples located sporadically within the whole section Site 1. A number of these samples felt or looked 'sandier' in the field, such as samples F1.10 and F1.12, which are location in the middle unit of diamicton (Facies 5) containing dense sand laminations, and F1.22 which had a sandy clay texture. Three out of the four samples taken from the weathered diamicton (Facies 7) at the top of the cliff at Site 2 also occur in this group. In addition, samples from the lower (Facies 1) and upper diamictons (Facies 3) at Site 3 are included in CF1. Three samples cluster as group CF2, sample F3.3, from the middle diamicton (Facies 2) at Site 3, and samples F1.13 (Facies 5) and F1.19 (Facies 6) from Site 1, where F1.13 also occurs in the sand laminated diamicton unit (Facies 5). Group CF3 consists of samples from only Site 1. All the samples originate from the lower unit of diamicton (Facies 4) at this site, except for F1.11, which was taken from the sand laminated diamicton above (Facies 5). The final group CF4 contains the remaining samples from the upper unit at Site 1 (Facies 6), and also includes the uppermost samples at Sites 2 and 3, F2.4 (Facies 7) and F3.5 (Facies 3).

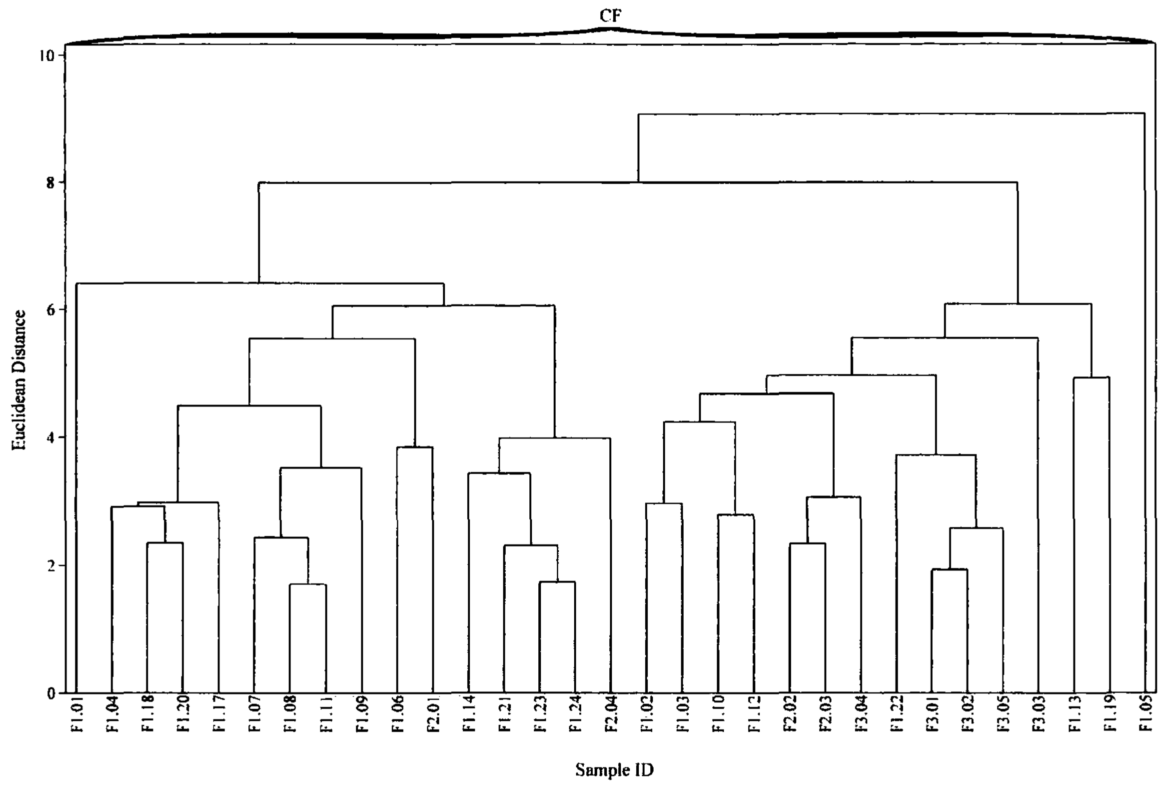


Figure 4.60. Filey diamicton, dendrogram of cluster analysis using complete linkage and combined z-scores.

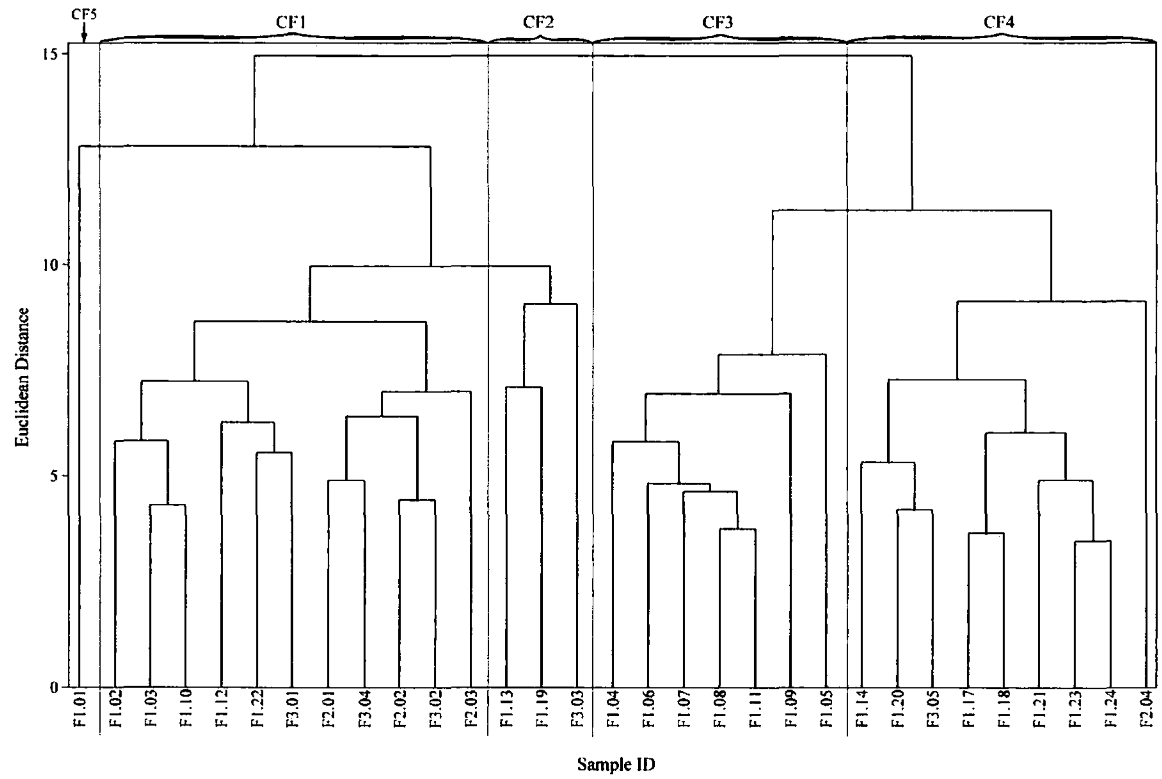


Figure 4.61. Filey diamicton, dendrogram of cluster analysis using complete linkage and individual z-scores.

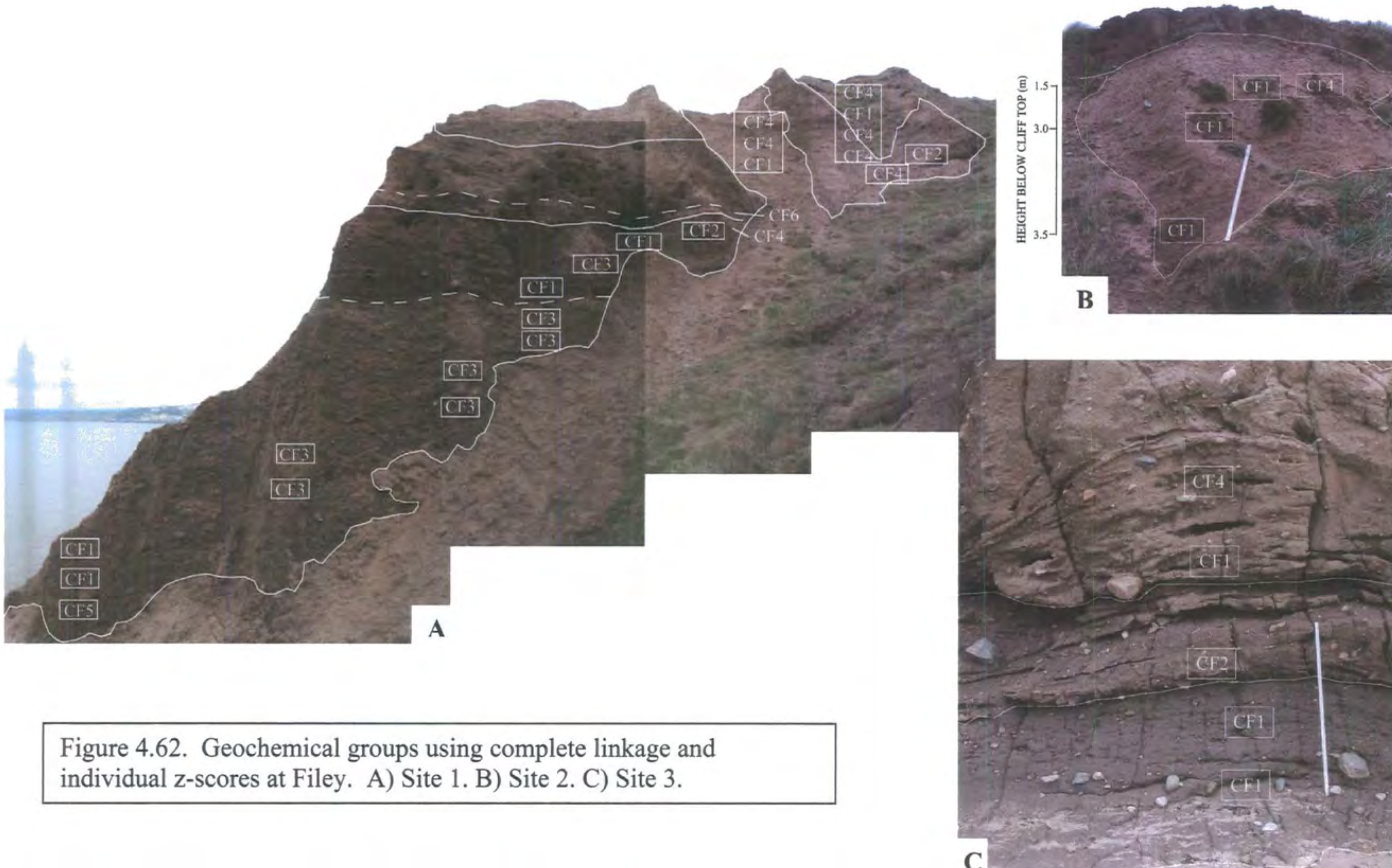


Figure 4.62. Geochemical groups using complete linkage and individual z-scores at Filey. A) Site 1. B) Site 2. C) Site 3.

Despite samples from CF1 and CF2 appearing 'sandier' in the field, abundances of Si, shown in Figure 4.45, shows that group CF1 is no higher in Si content than groups CF3 and CF4, and that CF2 is actually much lower. However, the apparent sandiness of these samples may indicate a change in grain size, rather than the addition of Si. Comparison of abundances of other elements (Figure 4.45) shows that groups CF3 and CF4 contain significantly higher abundances of a number of elements (Ti, Li, Be, V, Cr, Co, Ni, Nb, Ga, B and U) than groups CF1 and CF2. It is also interesting to note that CF3 contains much lower proportions of Ca than the other groups, but not of Sr, Ca's associated trace element. CF3 is also differentiated from the other groups by higher abundances of Rb, Y, Ce, Nd and Th (Figure 4.45).

Ward's Method

Using combined z-scores and a 'cut-off' dissimilarity level of squared Euclidean distance 100, as at Dimlington and Skipsea, samples at Filey are divided into two groups named WF and WG (Figures 4.63 & 4.65). Group WF is almost identical to groups CF3 and CF4, and contains diamictons from throughout Site 1, as well as including two samples from the weathered diamicton (Facies 7) at Site 2. Group WG contains the remainder of the samples at Site 1, many of which gave the impression, in the field, of being of a coarser texture. The group also contains the remaining two samples from Site 2 (Facies 7), and all of the samples from Site 3 (Facies 1, 2, and 3). Abundances of elements within the two groups are reasonably similar for many of the elements, however, there are a number of elements where group WF contains a greater abundance than group WG, including Ti, Fe, Al, Li, Be, V, Cr, Co, Ni, Nb, Ga, As and U (Figure 4.50).

Cluster analysis using individual z-scores at Filey divided the diamictons into four distinct groups, labelled WF1-WF4 (Figures 4.64 & 4.66). Group WF1 is very similar to the complete linkage group CF1, and contains samples from the lower diamicton unit at Site 1, the majority of samples from Site 2 (Facies 7), and samples F3.2 and F3.4 from the lower (Facies 1) and upper diamictons (Facies 3) at Site 3. Group WF2 contains the three samples found in group CF2, from Site 1 (Facies 5 and 6) and Site 3 (Facies 2), and three other samples F1.12 (Facies 5), F1.22 (Facies 6) and F3.1 (Facies 1). Samples within group WF3 all originate from the lower diamicton unit (Facies 4) at

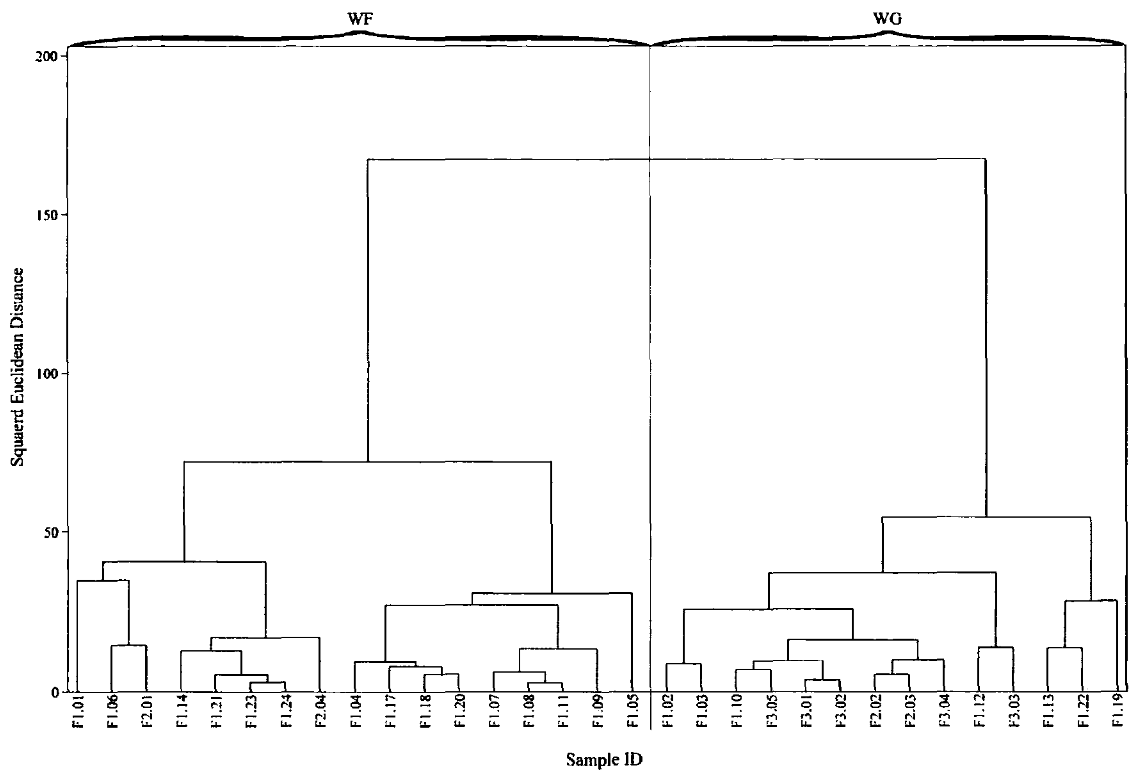


Figure 4.63. Filey diamicton, dendrogram of cluster analysis using Ward's method and combined z-scores.

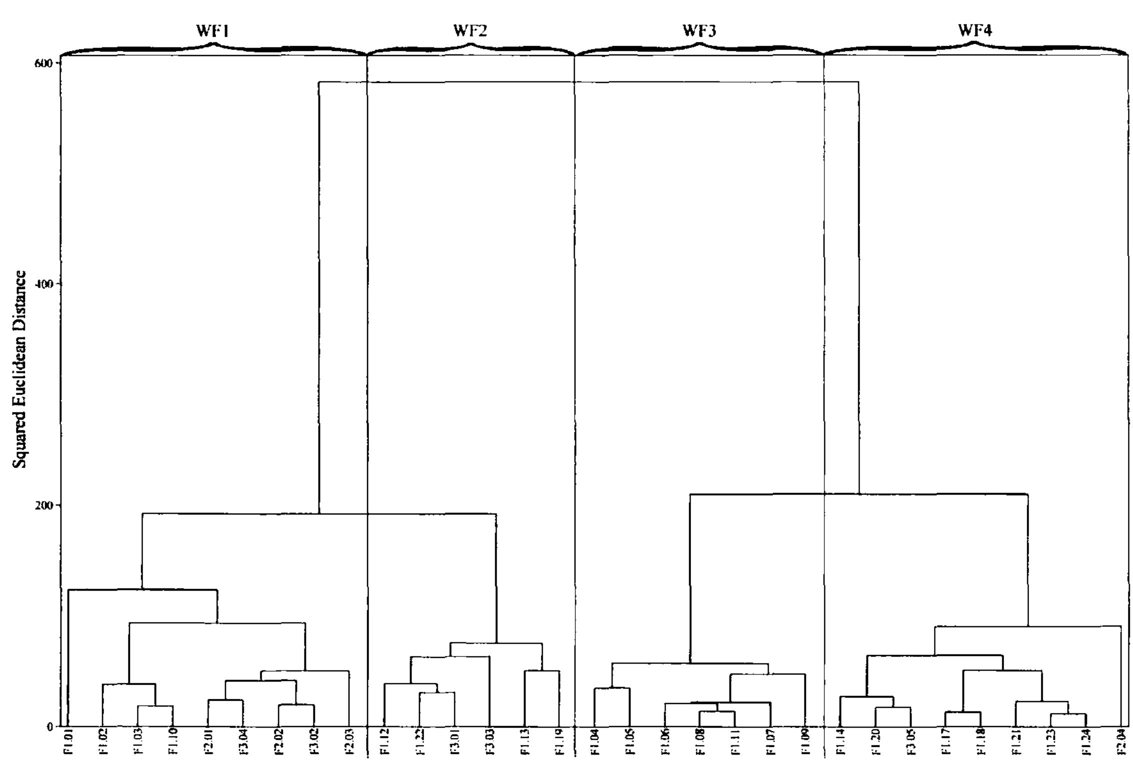


Figure 4.64. Filey diamicton, dendrogram of cluster analysis using Ward's method and individual z-scores.

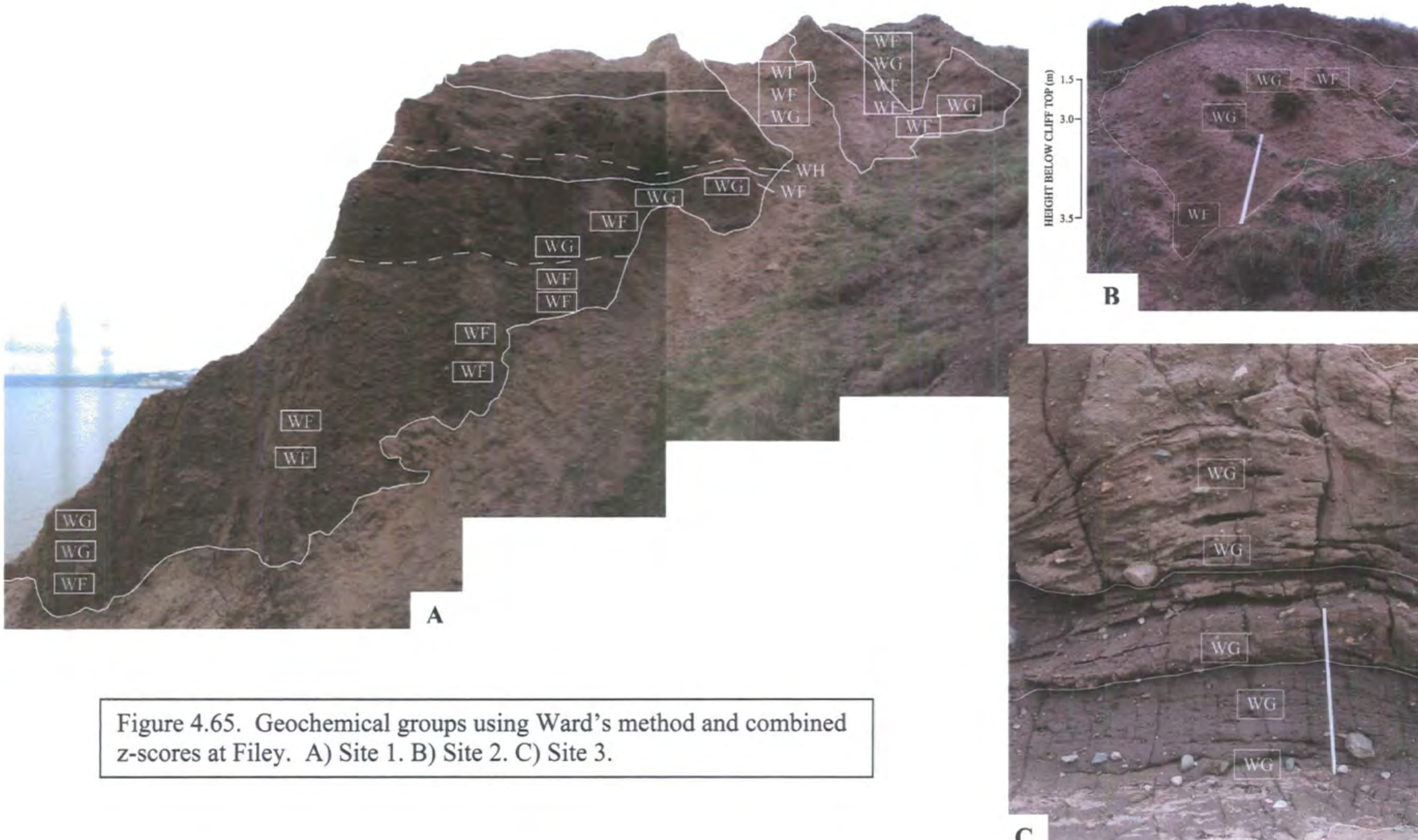


Figure 4.65. Geochemical groups using Ward's method and combined z-scores at Filey. A) Site 1. B) Site 2. C) Site 3.

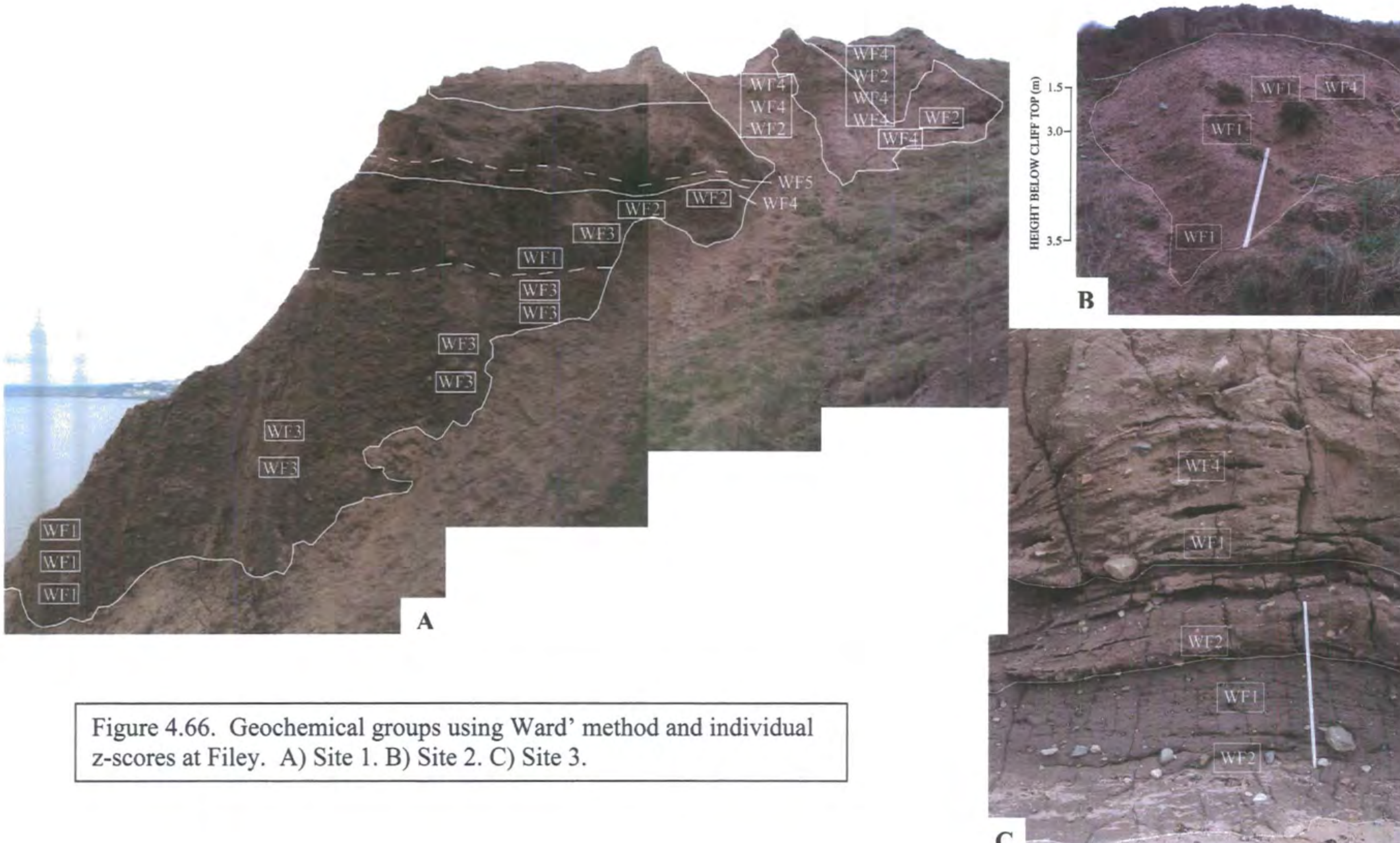


Figure 4.66. Geochemical groups using Ward' method and individual z-scores at Filey. A) Site 1. B) Site 2. C) Site 3.

Site 1, apart from F1.11, which is located in the laminated diamicton above (Facies 5). Samples in this group are identical to samples in the complete linkage group CF3, although the way in which these samples cluster together is different. Samples clustering to make group WF4 are also identical to those in group CF4 and also cluster with each other identically. These samples are mostly located in the upper diamicton unit at Site 1 (Facies 6). In general samples in groups WF1 and WF2 occur in the combined z-score group WG, whilst samples in groups WF3 and WF4 fall into WF.

Filey Overall

Overall, the cluster analysis shows that diamictons at Site 1 can be split into three groups; diamictons in the lowest massive section (Facies 4), diamictons in the upper massive unit (Facies 6), and diamictons in the laminated unit or those that exhibit a 'sandier' nature (Facies 5). Weathered diamictons (Facies 7) from Site 2 tend to correlate with the sandy diamictons (Facies 5), although this changes between cluster methods. Diamictons at Site 3 (Facies 1, 2 and 3) similarly also clusters in the same group as the sandy diamictons at Site 1 (Facies 5), although within this group they cluster most closely with each other, and those at Site 2 (Facies 8).

Filey Sands and gravels

One gravel sample, F1.15, and one sand sample, F1.16 were taken at Filey. F1.16 clusters with the 'sandy' diamictons, supporting the argument that these samples are distinguished by their coarser nature, possibly due to the presence of sand laminations within them, and is placed in group CF1 using the complete linkage method, and groups WG and WF2 using Ward's method. All four cluster methods showed the geochemical suite in sample F1.15 to be very different from the rest of the samples, clustering it at a much higher dissimilarity level than any of the other samples (see Appendix iii).

4.3.4 South Ferriby

Using the dissimilarity levels defined at Dimlington for combined z-scores (Euclidean distance 10 and squared Euclidean distance 100), both the complete linkage and Ward's methods cluster all South Ferriby samples together below these distances (Figure 4.67). As at Filey, this indicates that there is less variation in diamicton geochemistry at South

Ferriby than at Dimlington. However, the significantly smaller number of samples at this site compared to Dimlington is also likely to contribute to the reduction in variation. South Ferriby samples are therefore labelled as CJ for the complete linkage method, and WJ for Ward's method. The samples also cluster almost identically using the two methods (Figure 4.67).

Analysis using individual z-scores and the complete linkage method alters the cluster dendrogram slightly, placing sample SF2.1 as the least similar sample (Figure 4.67). Four groups of samples were identified from this clustering. The lower three samples at Site 1 (Facies 1 and 2) cluster together with sample SF2.3 from the upper diamicton (Facies 3) at Site 2 in group CSF1. Sample SF1.4 from the upper diamicton (Facies 3) at Site 1 is most similar to SF2.2 from the laminated diamicton unit (Facies 2) at Site2, and the two samples are labelled as group CSF2. Sample SF2.4 from weathered diamicton (Facies 4) is labelled as CSF3, and SF2.1 is named CSF4 (Figure 4.68).

Using individual z-scores and Ward's method, a cluster dendrogram is created that is identical to that produced by Ward's method using combined z-scores, and very similar to the complete linkage method dendrogram also using combined z-scores (Figure 4.67). Samples are divided into three groups using this method. Group WSF1 is almost identical the complete linkage group CSF1, except that it also includes sample SF2.1 (Facies 1), which is no longer the least similar sample in the cluster dendrogram. Group WSF2 is identical to group CSF2, and the weathered diamicton (Facies 4) in sample SF2.4 is again labelled separately as WSF3 (Figure 4.68).

South Ferriby Overall

Overall the cluster analysis shows that the lower diamicton (Facies 1) at Sites 1 and 2 is the same unit, and this is also geochemically very similar to the laminated diamicton unit (Facies 2) at Site 1. The laminated diamicton (Facies 2) at Site 2 contains denser sand laminations than at Site 1, which may be a reason why the two laminated samples do not cluster strongly. Instead it clusters with sample SF1.4 from the top of the upper diamicton (Facies 3) at Site 1 in which some weathering may have occurred. Sample SF2.4 (Facies 4) is very strongly weathered, and this sample shows the least similarity to any of the other samples, although it is most closely affiliated to the upper diamicton at Site 1 (SF1.4) (Facies 3), and the laminated diamicton at Site 2 (SF2.2) (Facies 2).

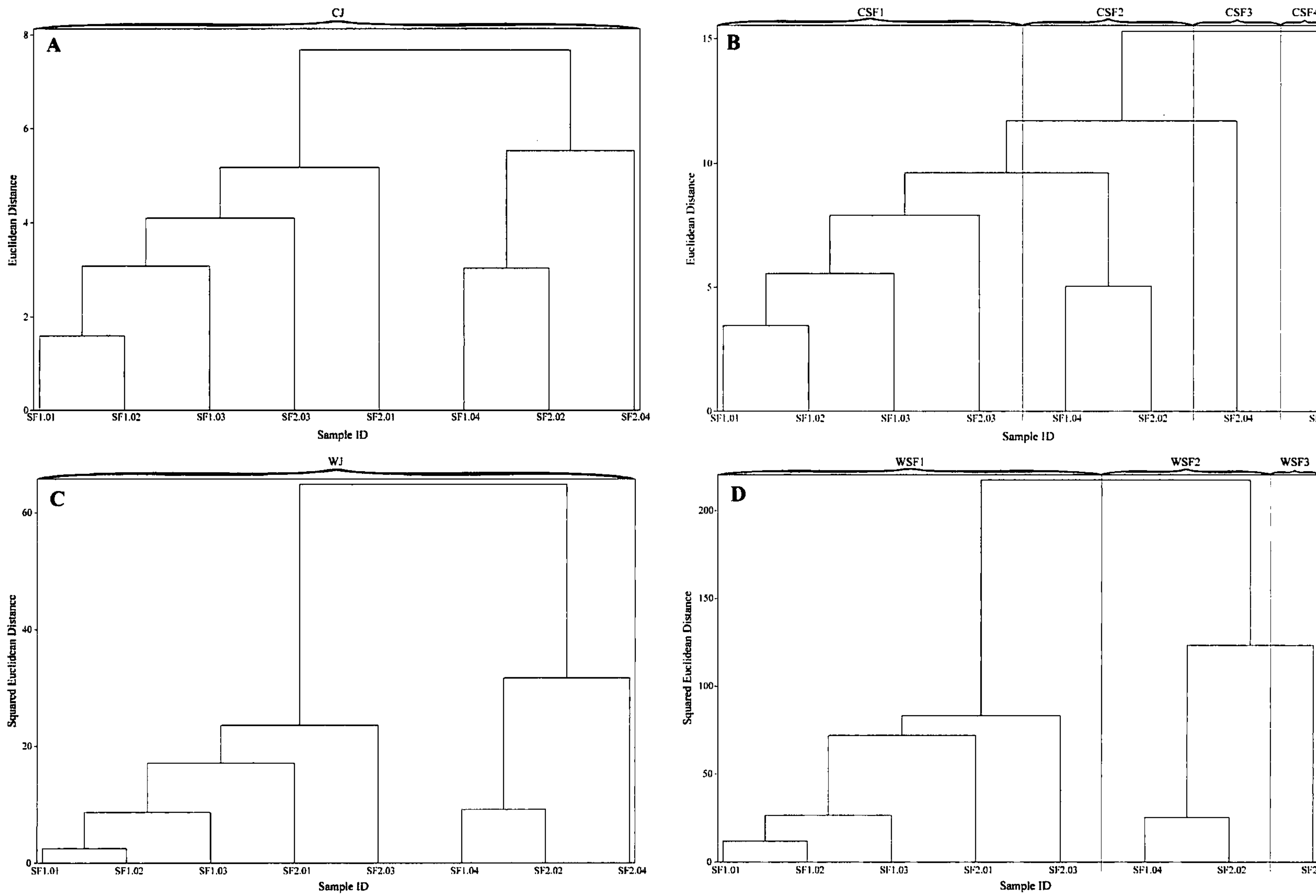


Figure 4.67. South Ferriby, dendrograms of cluster analysis using complete linkage A) combined z-scores, B) individual z-scores; Ward's method C) combined z-scores, D) individual z-scores.

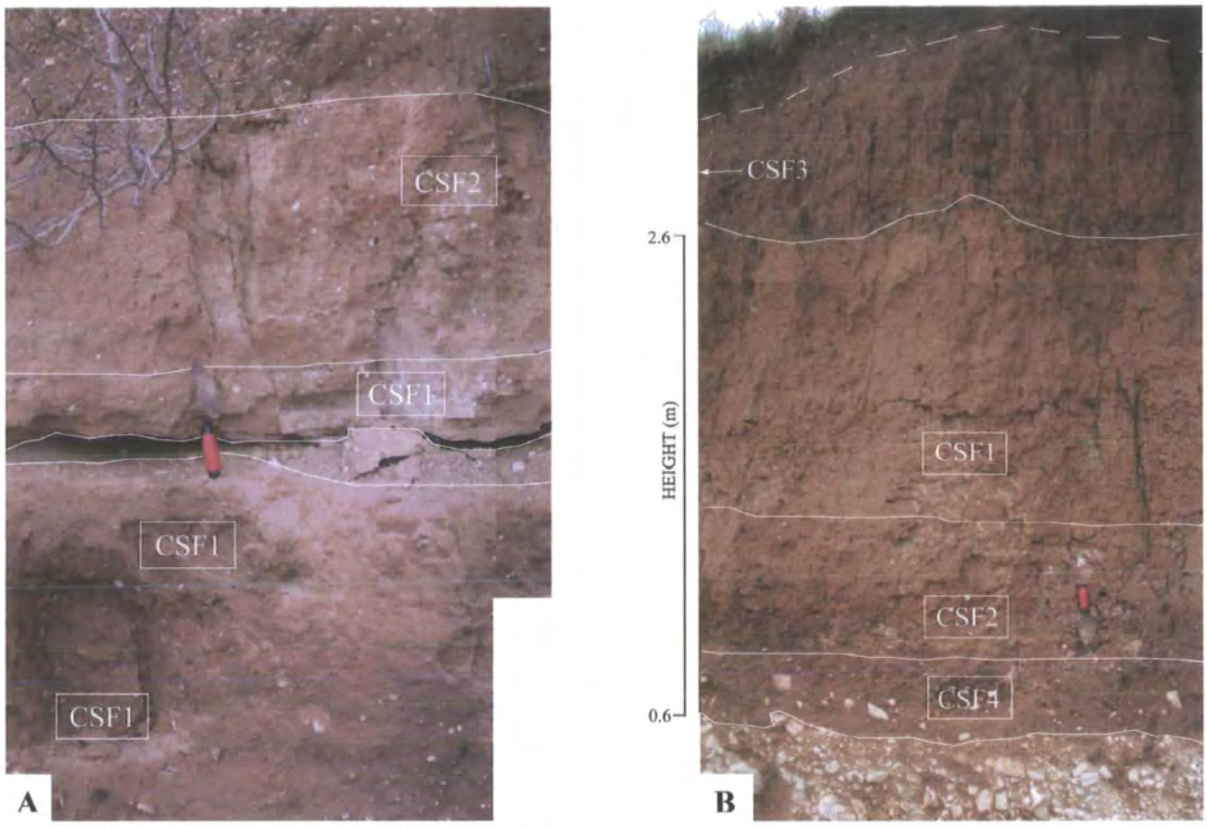
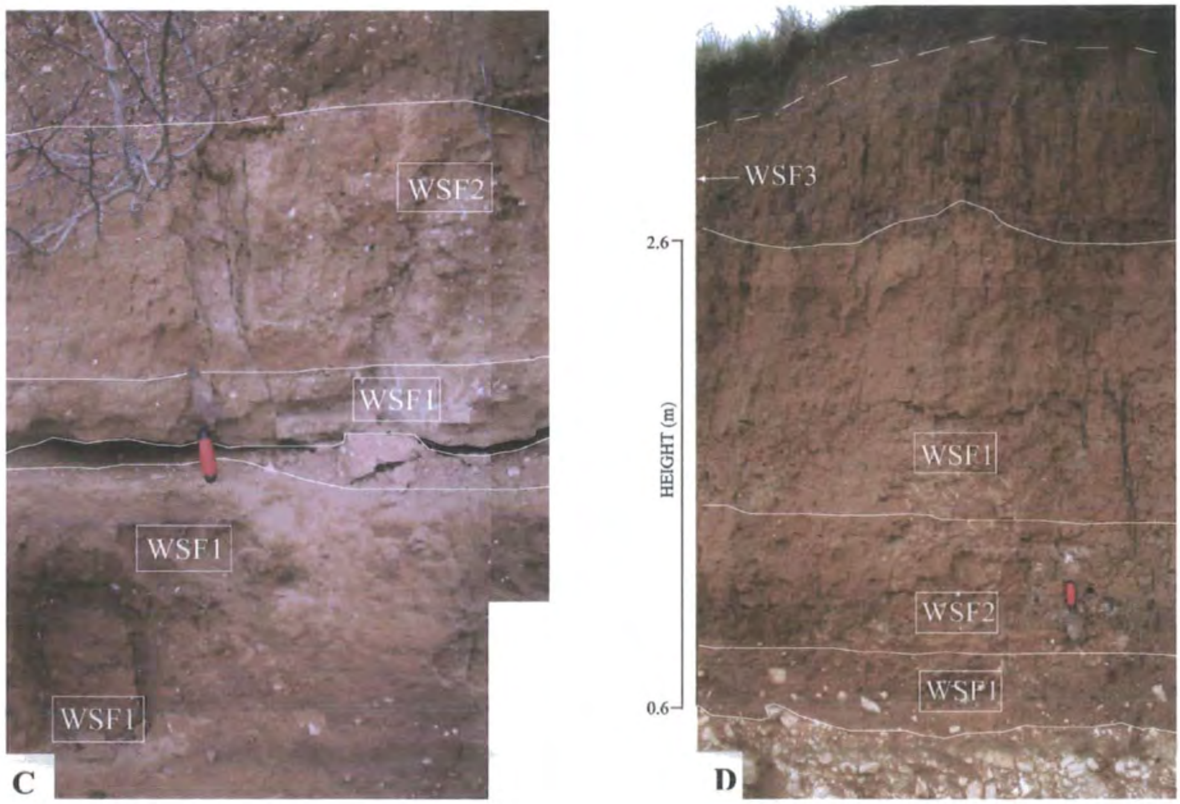


Figure 4.68. Geochemical groups at South Ferriby using: complete linkage and individual z-scores A) Site 1, B) Site 2; Ward' method and individual z-scores. C) Site 1, D) Site 2.



Using the three groups defined by Ward's method, group WSF2 is distinguished from WSF1 by higher abundances of K, Ti, Fe, Li, Be, V, Cr, Ni, Zn, Nb, Mo, Ga, Sn, B, As and U (Figure 4.51). As would be expected WSF3 tends to have more similar element abundances to WSF2.

4.3.5 Kirmington

Results from the four methods of cluster analysis at Kirmington demonstrate that the three samples taken here are very similar (Figure 4.70). Analysis using combined z-scores in both clustering methods, grouped the samples at a similarity well below the 'cut-off' level used for Dimlington, and much lower than the overall dissimilarity at South Ferriby and Welton-Le-Wold. The two methods also clustered the samples identically placing sample K1.2, the uppermost and most weathered (Facies 2) sample in the section as the least similar. Analysis using individual z-scores in both methods, however, clustered sample K1.1 from the middle of the section (Facies 1) as the least similar sample (Figure 4.70). The change in the way in which the samples cluster emphasises the similarity of them, and as a result groups from Kirmington are labelled CK for complete linkage and WK for Ward's method.

4.3.6 Welton-Le-Wold

Cluster analysis using combined z-scores for the complete linkage and Ward's methods also placed all samples at Welton-Le-Wold in the same group at the Euclidean distance of 10 and squared Euclidean distance of 100, indicating similarity between the diamictons here Figure 4.70). These groups are named CL for the complete linkage method, and WL for Ward's method. Whilst the actual clusters formed between samples are different using the two methods for combined z-scores, the clusters are identical for the two methods using individual z-scores, where the samples can be split into three groups (Figure 4.70). CW1 for complete linkage, or WW1 for Ward's method includes samples W1.1 (Facies 1) and W1.4 (Facies 2), and CW2 (WW2) contains W1.2, W1.3 (Facies 2) and W1.6 (Facies 3). Sample W1.5 (Facies 2) is the most dissimilar of any of the samples and is labelled CW3 or WW3 (Figure 4.71). It is unclear why this clustering occurs, since it was perceived that sample W1.1 would be of a different geochemical composition to the rest of the samples in the section, due to being derived from a darker diamicton (Facies 1) at the base. Sample W1.6 (Facies 3)

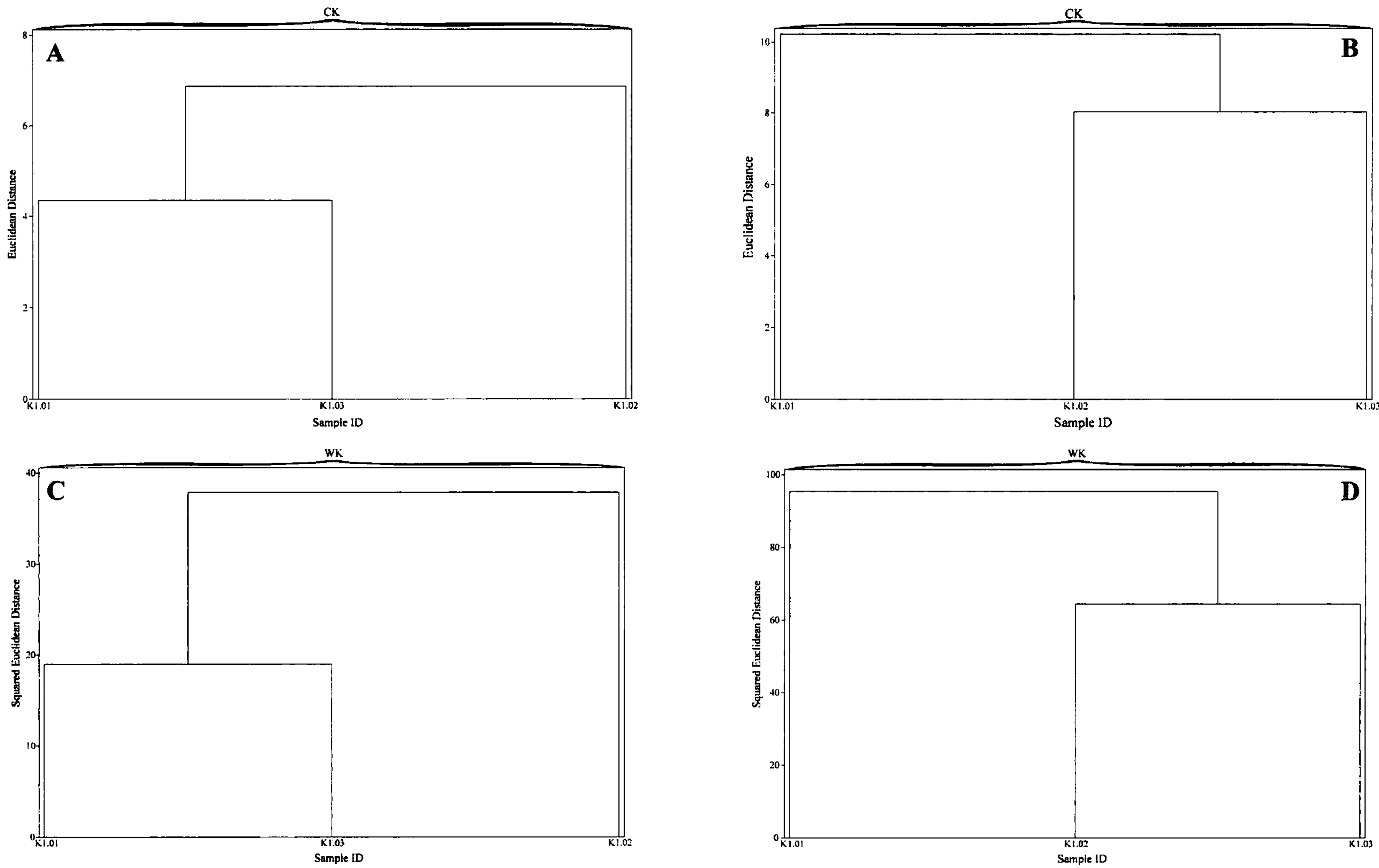


Figure 4.69. Kirmington, dendrograms of cluster analysis using complete linkage A) combined z-scores, B) individual z-scores; Ward's method C) combined z-scores, D) individual z-scores.

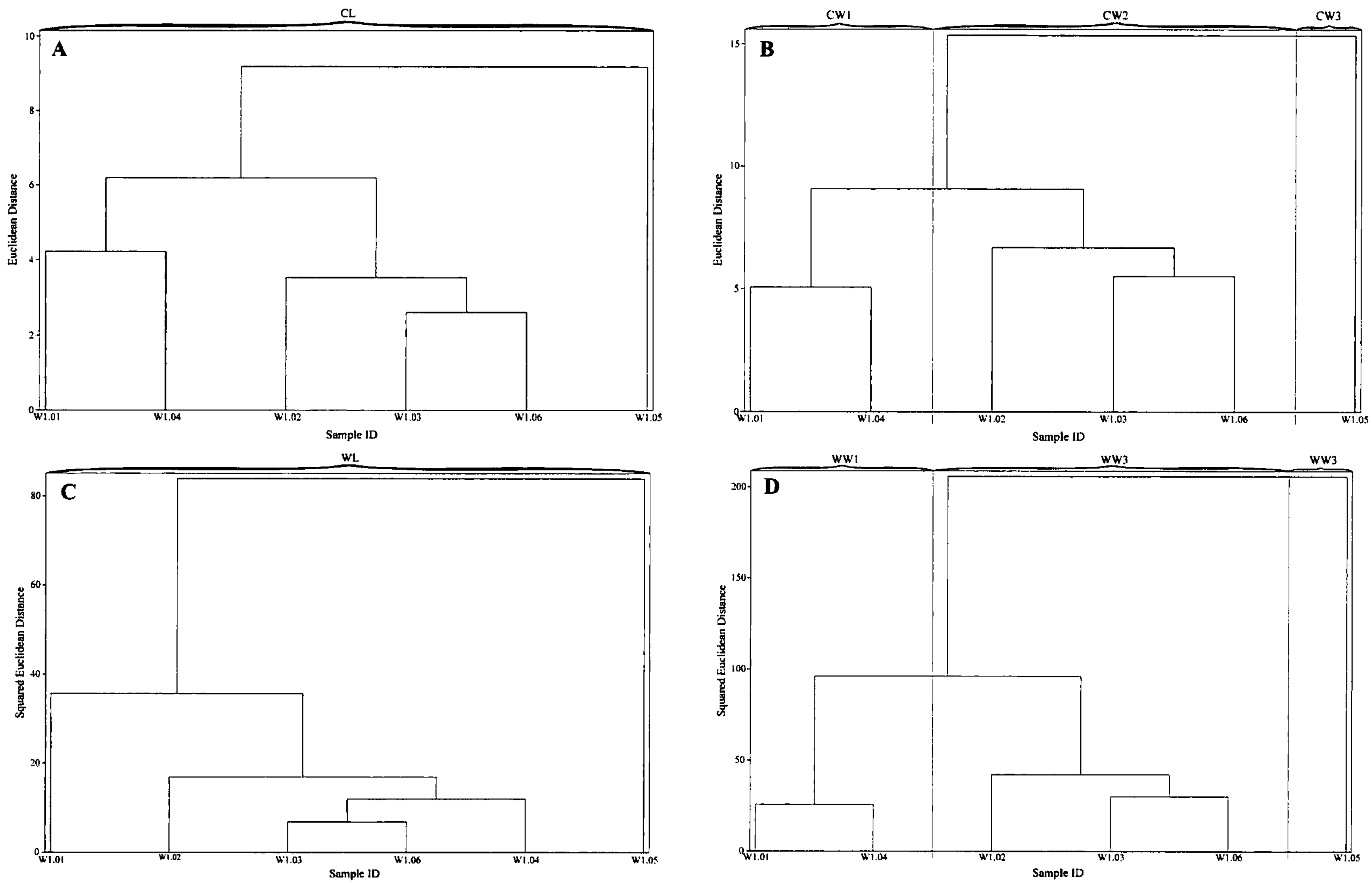


Figure 4.70. Welton-Le-Wold, dendrograms of cluster analysis using complete linkage A) combined z-scores, B) individual z-scores; Ward's method C) combined z-scores, D) individual z-scores.

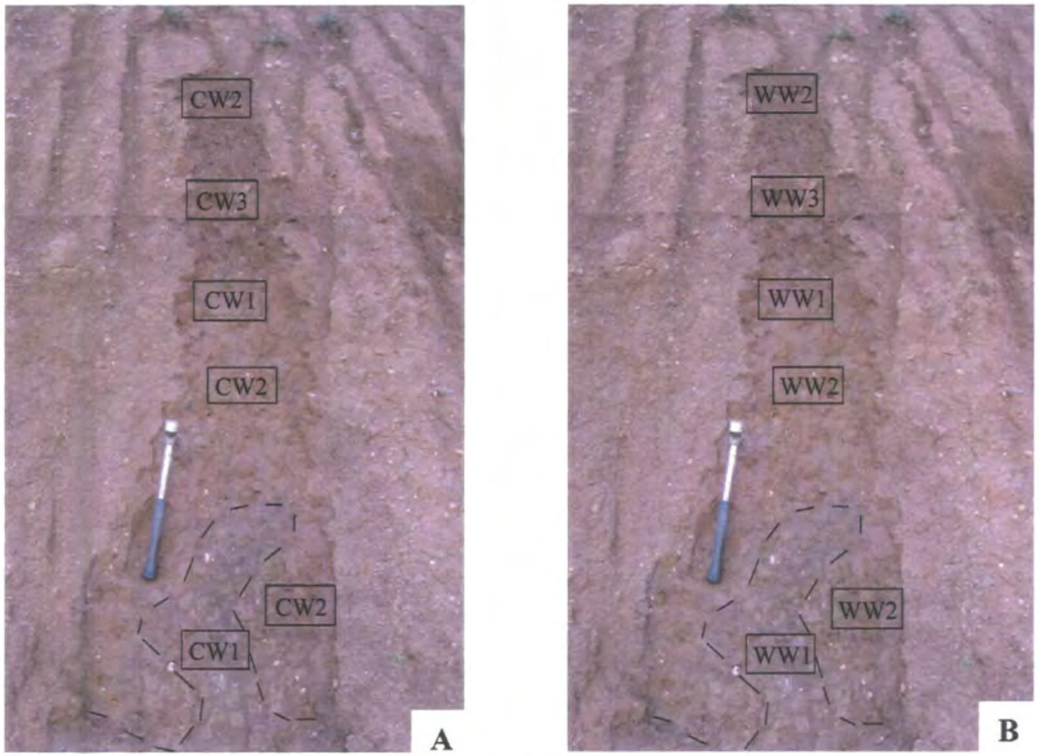


Figure 4.71. Geochemical groups at Welton-Le-Wold using: A) complete linkage and individual z-scores and B) Ward' method and individual z-scores.

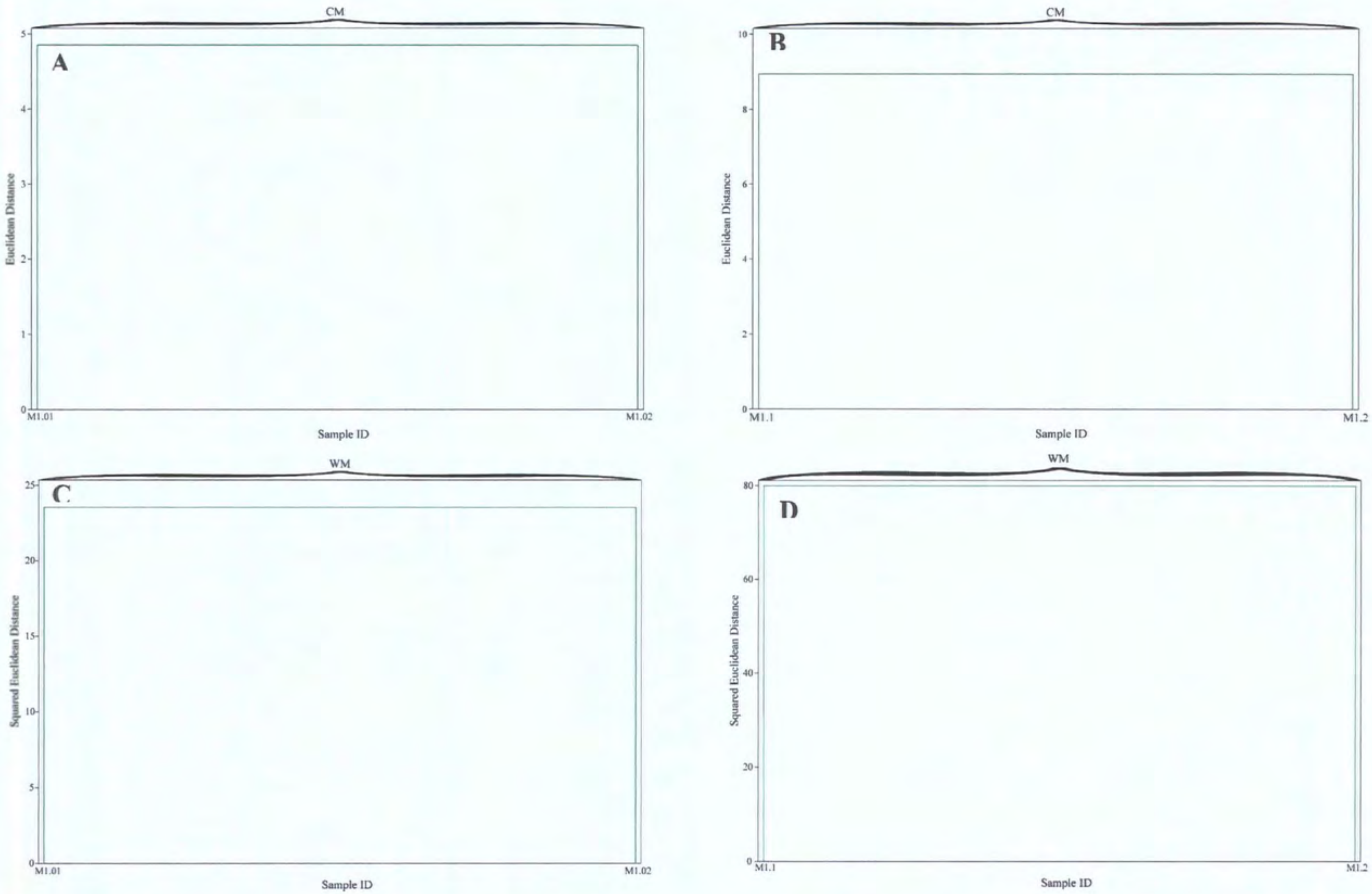


Figure 4.72. Morston, dendrograms of cluster analysis using complete linkage A) combined z-scores, B) individual z-scores; Ward's method C) combined z-scores, D) individual z-scores.

exhibited signs of weathering, and so was also expected to be different to the other samples, but cluster analysis shows it to be most similar to samples W1.2 and W1.3 towards the base of the section. Figures 4.45 and 4.1 show that group CW2 (WW2) contains lower abundances of Ti, Fe, Li, Be, Ba, V, Cr, Mn, Ni, Cu, Zn, Zr, Nb, Mo, Ga, and U than CW1 and CW3 (WW1 and WW3).

4.3.7 Morston

At Morston, the two samples clustered at Euclidean and squared Euclidean distances lower than the distances at which the five repeated D5.12 samples cluster (Section 3.5.1), illustrating a great similarity between the two samples, as may be expected from such a small section. These two samples are therefore grouped together as CM for the complete linkage method, and WM for Ward's method (Figure 4.72).

4.3.8 Comparison of Study Sites

Average abundances of each element were calculated for each group of samples described above, in each method of cluster analysis. Cluster analysis was then performed on these group averages in order to compare samples at different locations. The results are shown in Figures 4.73 – 4.76 and summarised in Figures 4.77 and 4.78.

In general the geochemical groups cluster in a chain-like fashion, where the groups can not be divided into distinct clusters, perhaps indicating an overall similarity of the diamictons in all seven locations. The five main groups recognised at Dimlington using Ward's method, generally remain intact in this cluster analysis. Groups WD1 and WD2 (WY & WZ), which contain the dark grey-brown diamictons at Sites 2, 3 and 4 (Dimlington Facies 2 (DF2)) and the weathered diamicton at Site 1 (DF8), cluster within close proximity to each other, and show a similarity with group WD10 (WV) which represents the weathered diamictons in the upper section at Dimlington Site 5 (DF8) and the lower diamicton at Dimlington Site 6 (DF9). This group of samples also shows an affinity with the majority of samples from Filey Site 1 (DF4, DF5, DF6), the laminated diamicton (DF2) at South Ferriby Site 2, and a number of samples at Welton-Le-Wold (W1.1 and W1.4 (Welton 2) (Figures 4.77 and 4.78).

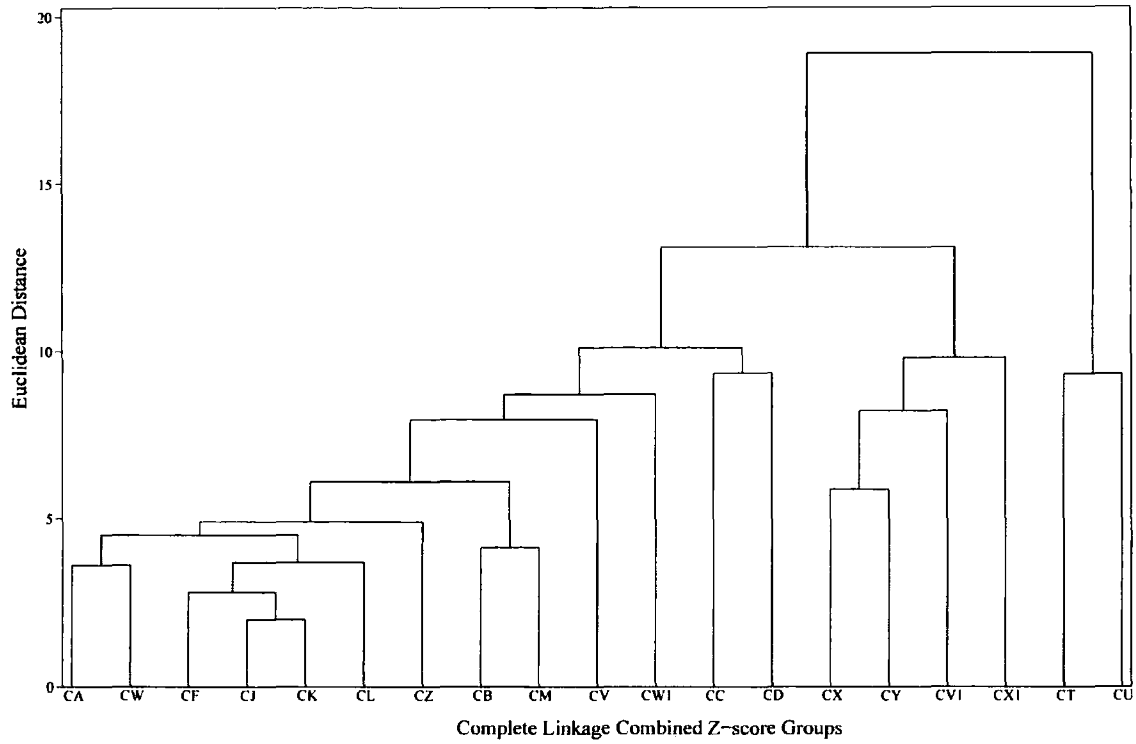


Figure 4.73. Geochemical groups for all sites: dendrogram of cluster analysis using complete linkage and combined z-scores.

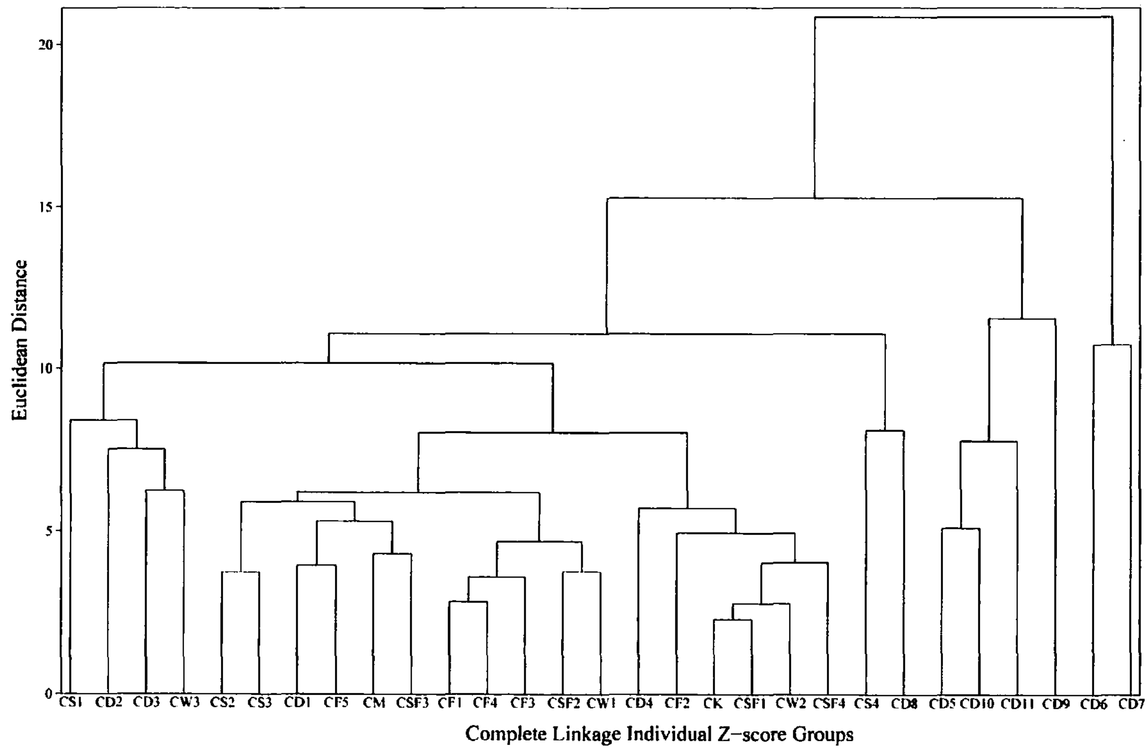


Figure 4.74. Geochemical groups for all sites: dendrogram of cluster analysis using complete linkage and individual z-scores.

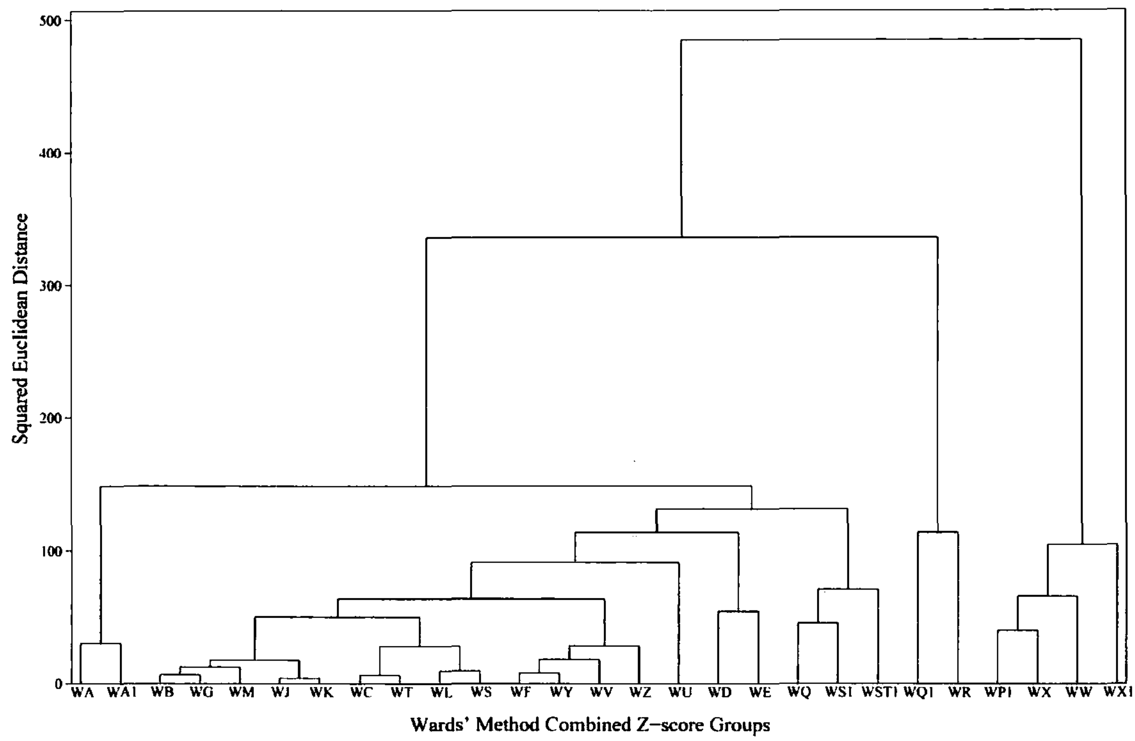


Figure 4.75. Geochemical groups for all sites: dendrogram of cluster analysis using Wards' method and combined z-scores.

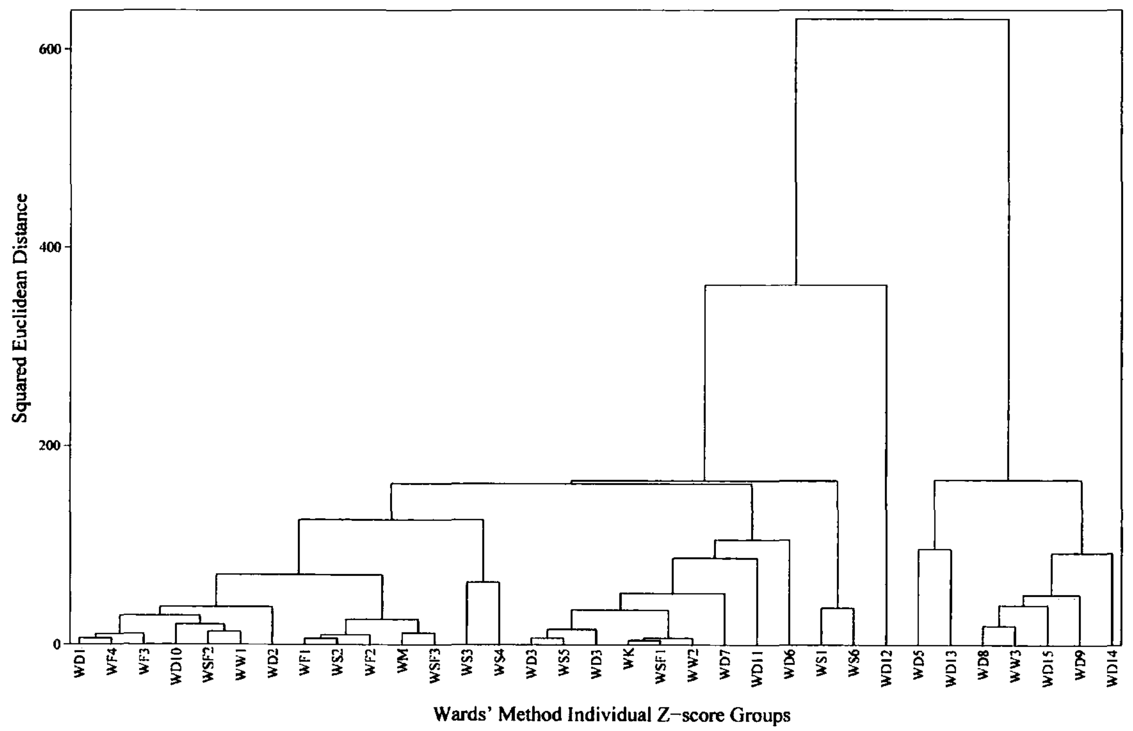


Figure 4.76. Geochemical groups for all sites: dendrogram of cluster analysis using Wards' Method and individual z-scores.

Dimlington groups WD3 and WD4 (WT & WS), which, in general, contain chalk-rich, dark grey/brown diamictons from Sites, 2, 3 (DF1), and 5 (DF7) cluster closely with the upper diamicton units at Skipsea Sites 2 and 3 (SF2 and SF3), and a number of samples from the upper diamicton at Skipsea Site 1 (SF2), all of which also contain high abundances of chalk and limestone clasts. This group of samples also clusters well with other samples at Welton-Le-Wold (W1.2, W1.3, W1.6 (Welton 1), the diamicton at Kirmington, and the lower diamicton at South Ferriby (SFF1) (Figures 4.77 and 4.78).

The upper diamicton at Site 6 (DF10) and diamicton at Site 10 (DF2 and DF11), Dimlington (group WD5/WU), tend not to cluster closely with any other group. However, this group does join other cluster groups at a relatively low Euclidean or squared Euclidean distance, indicating that although it does not show a great affinity with any of the other groups, it does contain a reasonably similar suite of elements. This is illustrated by the original group CD2 formed using the complete linkage method and individual z-scores, where the upper diamicton at Site 6 (DF10) and the diamicton at Site10 (DF2 and DF11) are grouped with the weathered diamicton from the upper section of Site 5 (DF5) and samples from the basal unit at Site 6 (DF9).

The light brown chalky diamictons (DF3) at Dimlington (groups WD6 (WR) & WD7 (WQ)) cluster closely together in the overall cluster analysis, and in most of clusters, combine with other groups late in the cluster chain. Ward's method, individual z-score analysis, however, does show that the group has an affiliation with the dark brown chalk-rich diamictons (DF1) at Dimlington (groups WD3 & WD4), as well as with samples from the upper diamictons at Skipsea Sites 1, 2 and 3 (SF2 and SF3), and samples from Welton-Le-Wold (Welton 1) and the lower diamicton at South Ferriby (SFF1) (Figures 4.77 and 4.78).

The final group identified at Dimlington includes samples from the lower diamicton at Site 5 (DF5 and DF6) (WD9/WW), samples from the middle of the Site 5 section (DF7) (WD8/WX), and samples from the weathered upper diamicton at Site 5 (DF8) (WD10/WV). However, the subsequent cluster analysis shows that although groups WD9 (DF5 and DF6) and WD8 (DF7) continue to cluster closely, group WD10 (DF8) shows a strong affiliation with groups WD1 and WD2 which contains dark diamictons from Sites 2, 3, and 4 (DF2) and the weathered diamicton from Site 1 (DF8), as discussed above. Samples from the lower and middle diamictons at Site 5 (DF5 and

DF6) still, however, show a strong similarity with each other, and several of the overall clusters show them as being relatively dissimilar to any other groups. The original cluster analysis does, however, demonstrate that the diamictons show some similarity to the upper diamicton at Site 5 (DF8), and the diamictons at Sites 6 and 10 (DF9, DF10, DF11) (groups CD2 and CD3) (Figures 4.77 and 4.78).

As discussed above, the upper diamictons at Skipsea Sites 2 and 3 (SF2 and SF3), and some samples from the upper unit at Site 1 (SF2) show a great similarity to the chalk-rich dark-grey diamictons at Dimlington Sites 2, 3 (DF1) and 5 (DF7). Samples from the lower diamicton at Skipsea Sites 3 and 4 (SF1) cluster with other samples from the upper diamicton at Site 1 (SF2), and the subsequent overall cluster analysis shows this group to be very similar to the upper diamicton unit at Skipsea Site 3 (SF3), as well as the coarse samples at Filey Site 1 (FF5), samples at Filey Site 3 (FF1, FF2, FF3), and the diamicton at Morston (MF1 and MF2) (Figures 4.77 and 4.78).

The overall cluster analysis shows that the lower diamicton at Skipsea Site 1 (SF1) displays a lack of great similarity with any other groups, particularly using Ward's method. The cluster dendrograms produced from complete linkage groups do, however, show this unit to be weakly similar to the dark brown diamictons at Dimlington Sites 2, 3 and 4 (DF2), and the weathered diamicton at Site 5 (DF8) (Figures 4.77 and 4.78). Overall cluster analysis also demonstrates that diamicton bands (SF4) within the sand cavity at Site 4 are not greatly similar to any other groups, although the complete linkage method does show this group as having some affinity with samples S3.3 (SF1), S3.7 (SF3) and S4.8 (SF5) at Skipsea. Nonetheless, overall, this group does cluster with the main cluster group at a relatively small Euclidean distance, and therefore its geochemical composition must possess some similarity to that of other groups.

At Filey, the upper (FF6) and lower diamictons (FF4) at Site 1 cluster together in the overall analysis, and show a similarity to the dark brown diamictons at Dimlington Sites 2, 3 and 4 (DF2), and some weathered samples from Dimlington Site 1 (DF8). The 'sandy' diamicton at Filey Site 1 (FF5), which is generally previously clustered with the diamictons at Sites 2 (FF7) and 3 (FF1, FF2, FF3) at Filey tends to cluster closely with the upper diamicton (SF2) at Skipsea Site 1 and the lower diamicton (SF1) at Site 3, as discussed above, and shows some similarity to the laminated diamicton unit (SFF2) at

South Ferriby Site 2, and samples from the diamicton at Welton-le-Wold (Welton 2) and Morston (MF1 and MF2) (Figures 4.77 and 4.78).

Groups of samples from Lincolnshire tend to cluster closely together in the overall cluster analysis. The diamicton at Kirmington displays a strong similarity to the lower diamicton unit at South Ferriby, and samples W1.2, W1.3 and W1.6 (Welton 1)at Welton-Le-Wold. The cluster analysis following the complete linkage method and using individual z-scores also links this grouping the dark grey/brown chalky diamictons at Dimlington Sites 2, 3, 4 (DF1) and 5 (DF7), whilst Ward's method using combined z-scores links Kirmington and South Ferriby diamictons with the diamicton at Morston, the 'sandy' diamictons at Filey Site 1 (FF5) and diamictons at Filey Site 3 (FF1, FF2, FF3), the lower diamicton at Skipsea Sites 3 and 4 (SF1), and samples from the upper diamicton at Skipsea Site 1 (SF2) (Figures 4.77 and 4.78).

In cluster analysis using individual z-scores, where the weathered diamicton (SFF4) at South Ferriby (sample SF2.4) is differentiated as a separate group, overall cluster analysis groups this sample closely to the diamicton at Morston highlighting the weathered nature of the diamicton at this site. In clusters where sample SF2.4 is included in the main South Ferriby group, the Morston group (CM/WM) clusters with the 'sandy' diamictons at Filey (FF5), and diamicton at Filey Site 3 (FF1, FF2, FF3), as well as samples from the upper diamicton at Skipsea Site 1 (SF2) and the lower diamicton at Skipsea Site 3 (SF1) (Figures 4.77 and 4.78).

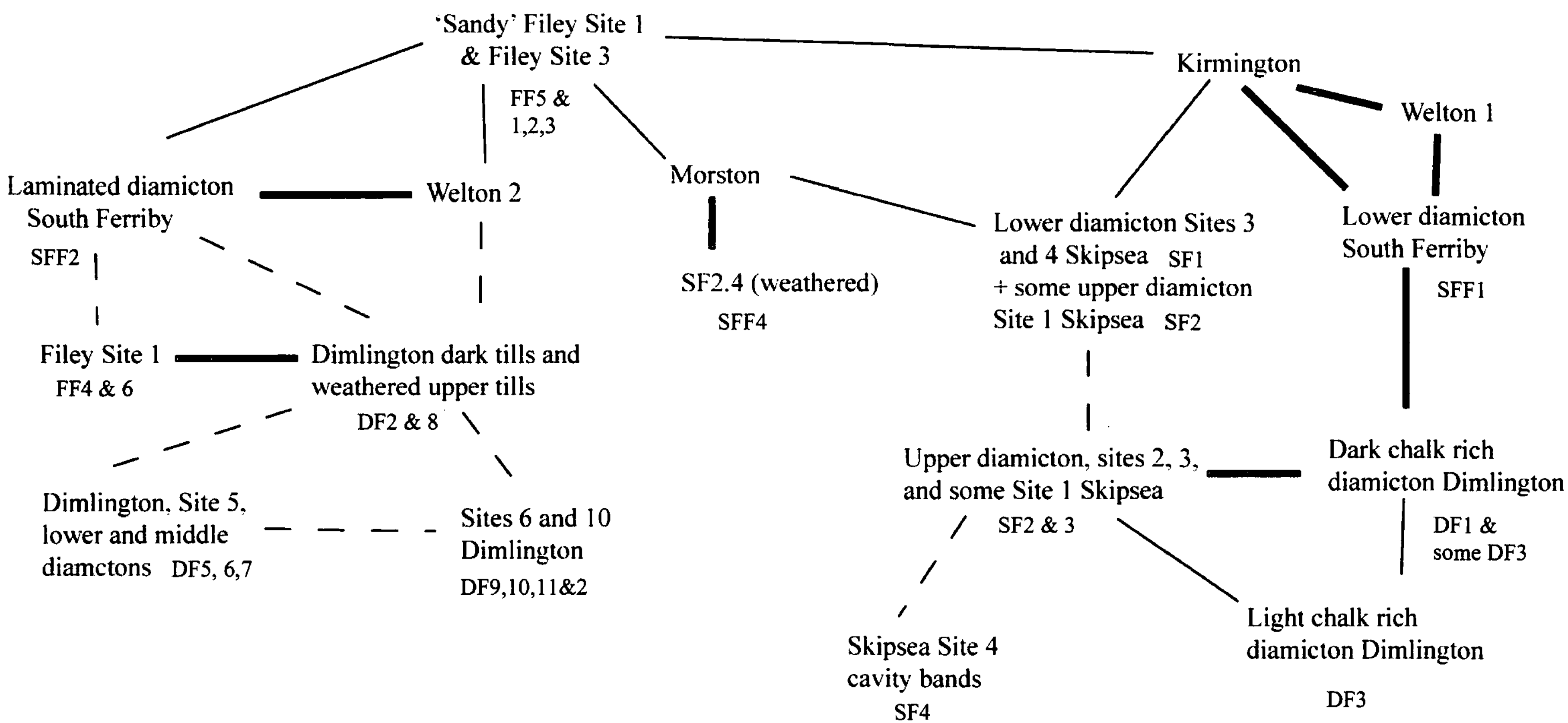


Figure 4.77. Spider diagram illustrating the overall geochemical similarities of pre-defined geochemically similar groups of diamictons at all seven study sites. Thick lines indicate a strong affinity between groups, and dashed lines represent a weaker similarity.

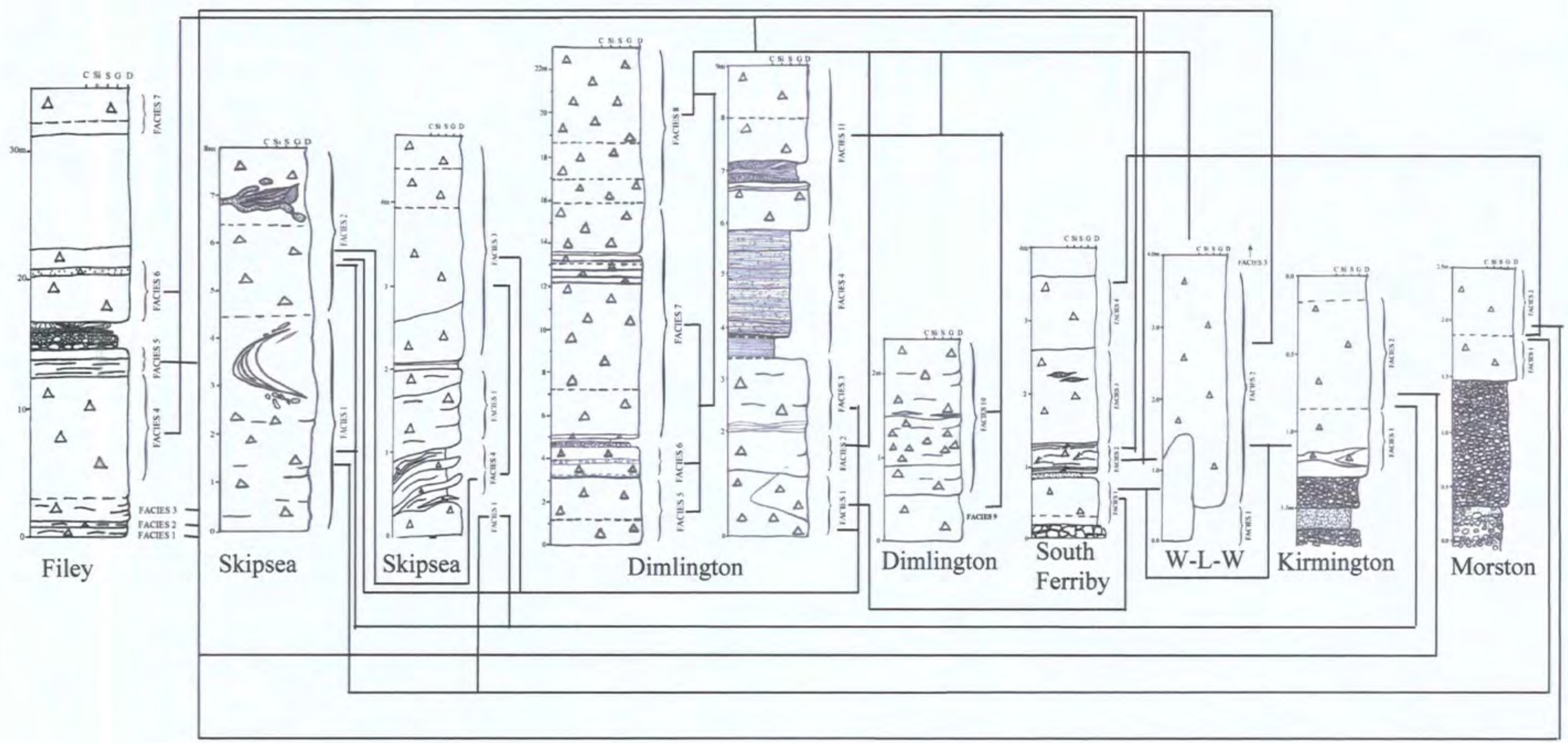


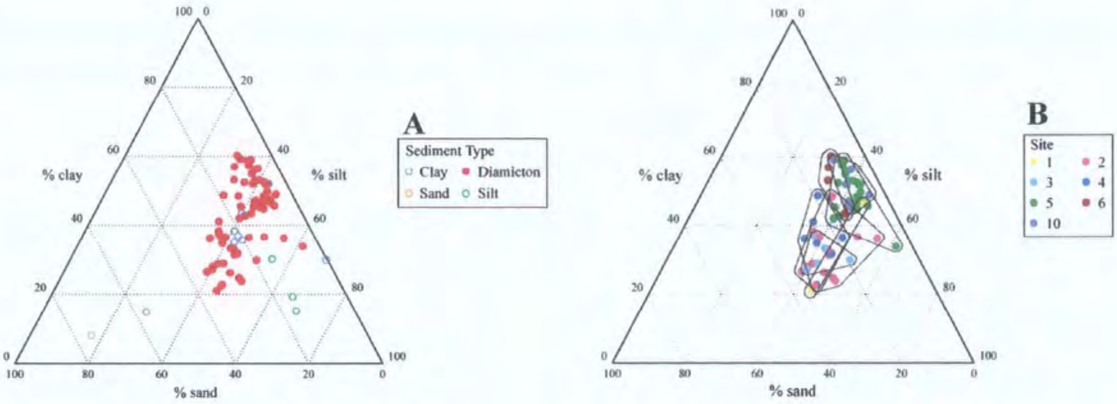
Figure 4.78. Composite stratigraphic diagram illustrating firstly how units at each site correlate vertically with each other and secondly how units cross correlate across all seven sites.

4.4 Particle Size Analysis

4.4.1 Dimlington

Particle size data reveals that the diamicton samples at Dimlington contain 21-61% clay, 30-61% silt and 4-35% sand. Errors associated with the detection of coarser particles by the coulter granulometer (*cf.* Section 3.5.2) mean that the particle size distributions displayed in Figure 4.79 may under represent the proportions of sand-sized (62.5-2000μm) particles. Therefore, control samples from clay, silt and sand units at Dimlington are used in Figure 4.79 to demonstrate that the diamicton at Dimlington contains, in general, a similar particle size distribution to clay units at the site. Particle size distributions at Dimlington form two adjoining clusters, one containing more sand and less clay than the other. However, Figure 4.79 shows that one cluster contains mainly samples from Sites 1-4 (batch 1), whilst the other consists of samples from Sites 5, 6 and 10 (batch 2). As discussed in Section 3.5.2, the temperature of the water in which the samples were analysed may be a possible cause for this difference.

Investigation of differences in particle size distribution between different diamicton units (Figure 4.78) reveal mixed results, where some facies show a close relationship between samples taken from within that unit, whilst other facies show a wide range of particle size distributions within them. The best example of significant particle size differences between units is at Site 6, where the three samples taken from the lower diamicton (Facies 9) possess very similar proportions of clay, silt and sand, which are distinctly different from the particle size distributions in the diamicton unit above (Facies 10), which also displays great similarity between the samples taken there. Particle size distributions of samples from other units, such as Facies 7, from the middle of the Site 5 section, the upper diamictons at Sites 1 and 5 (Facies 8), and the red-brown diamicton at Site 10 (Facies 11) are also similar within each unit, but the overlap between units is also great, and therefore it is impossible to differentiate the units by particle size. Samples from other units, such as Facies 2 and 3 show vast differences in their particle size distributions. Particle size analysis at Dimlington therefore demonstrates that although there may be differences in the particle size distributions of different diamicton units, the differences are generally not significant enough to enable differentiation of diamicton units through particle size analysis alone.



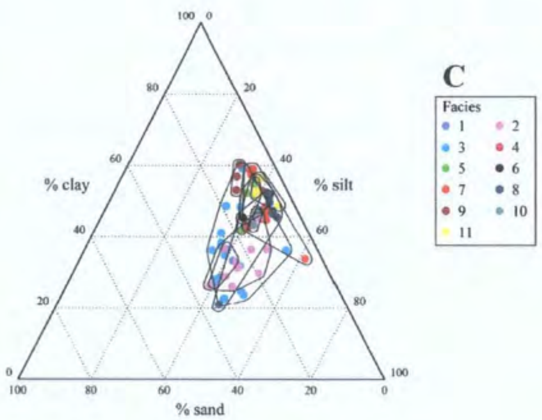
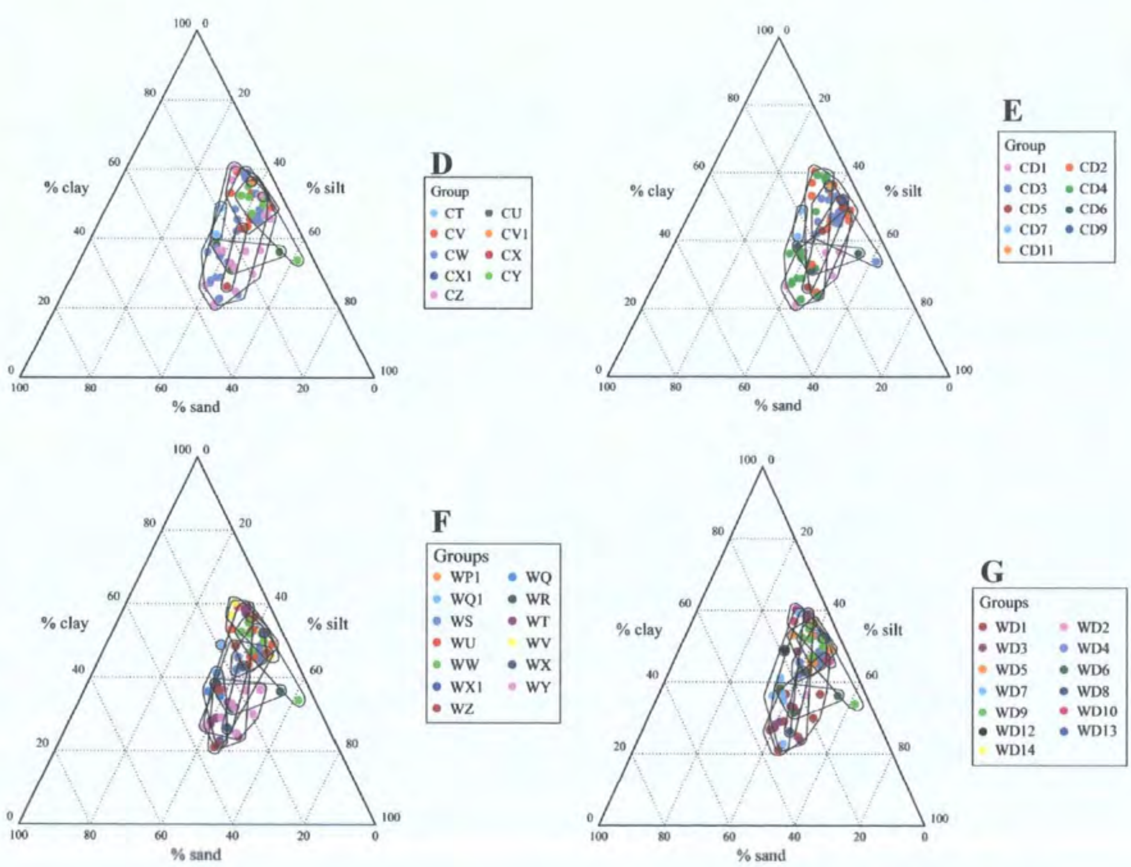


Figure 4.79. Particle size distributions of Dimlington samples by A) sediment type, B) site, C) facies, D-G) geochemical group.



Comparison of the particle size data with geochemical groups for the diamicton samples demonstrates that there is little relationship between the two. Triplots displaying Dimlington diamicton particle size distributions, which are differentiated by geochemical groups for each of the four cluster analysis methods (Figure 4.79) show that the proportions of clay, silt and sand are wide ranging within each group. This demonstrates that there is little relationship between diamicton groups based upon matrix geochemistry and particle size distributions.

4.4.2 Skipsea

Results of particle size analysis from Skipsea reveal that the proportions of clay-sized particles range from 14-32%, silt-sized from 33-53%, and sand-sized from 15-51%. Figure 4.80, using control samples from sand and clay units at Skipsea, again demonstrates that the diamicton at this location contains a similar particle size distribution to that of the clay sediments.

Examination of particle size distributions within each diamicton unit at Skipsea show that diamictons from the lower sections at Sites 1 and 3 (Facies 1) possess broadly similar ranges of particle size, which overlap significantly with the range of particle sizes in Facies 2 from the upper diamicton at Sites 1 and 2 (Figure 4.80). Facies 3 and 4 do, however, show some differences in particle size range to the majority of the samples. Facies 3 represents the upper diamicton at Site 3, which displays a lower proportion of sand, and a higher proportion of clay than all the other samples. The three samples from Facies 4 were taken from the bands of diamicton within the sand cavity at Site 4, and display very similar particle size distributions, which contain slightly higher percentages of clay than the main cluster of samples.

Differentiation of particle size distributions by geochemical groups defined in Section 4.2 shows a similar pattern to that differentiated by facies (Figure 4.80), since the geochemical groups at Skipsea show some affiliation with the diamicton units found. Again, particle size distributions within the geochemical groups vary, and overlap significantly with each other. Therefore, although here, particle size distributions are weakly associated with geochemical characteristics, they cannot be used to differentiate the geochemical groups.

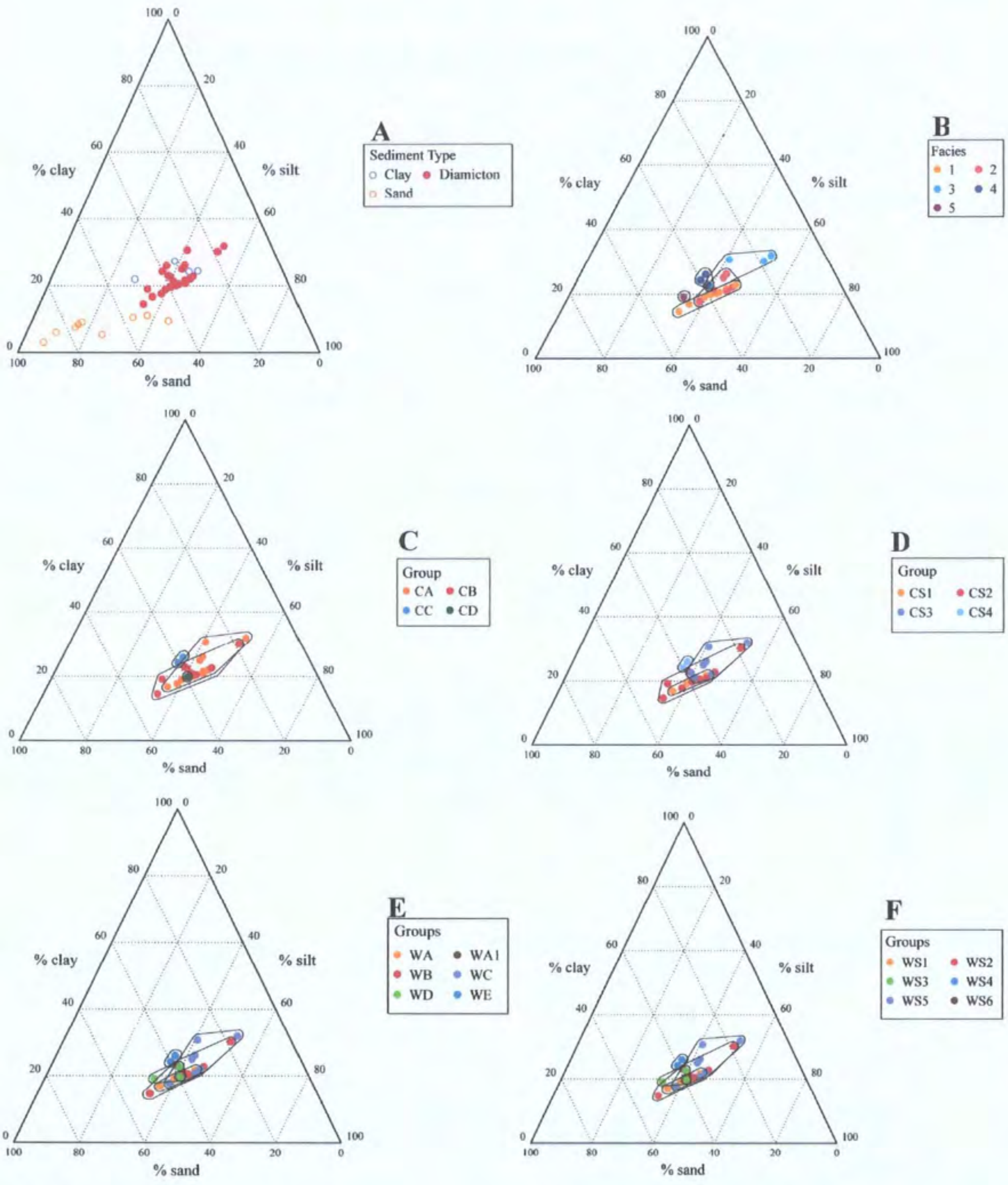


Figure 4.80. Particle size distributions of Skipsea samples by A) sediment type, B) facies, C-F) geochemical group.

4.4.3 Filey Brigg

Particle size analysis at Filey shows that diamictons at this location contain 26-49% clay, 44-56% silt, and 5-19% sand. Figure 4.81 reveals that a number of diamicton units at Filey contain very similar and distinct particle size ranges. These are: Facies 1 at the base of Site 3, where the two diamicton samples are almost identical; Facies 4, containing the lower diamicton at Site 1; and Facies 6, containing the upper diamicton at Site 1. Only one sample (F1.22) within Facies 6 displays a different particle size distribution. This sample was noted in the field as being of a coarser nature than the surrounding diamicton, and particle size analysis shows that the sample contains a higher proportion of silt, and a slightly higher percentage of sand than the rest of the samples in the unit. Samples taken from the laminated diamicton unit (Facies 5) at Site 1, exhibit a wide variety of particle size distributions, which vary mainly in sand and clay content. Facies 3 and 7, from the upper diamicton at Site 3 and the section at Site 2, respectively, also show variations between the samples, but the limited numbers of samples taken within these facies means that this cannot be clarified as characteristic of each facies as a whole.

Investigation of the relationship between geochemical groups and particle size distribution also reveals some noteworthy clusters. The similarity of particle size distributions within geochemical groups is not as distinct as within the diamicton units, but Figure 4.81 demonstrates that that some groups do contain samples with very similar particle size ranges. Samples from groups CF3(WF3) and CF4(WF4) are closely located on the particle size triplots, and although there is some overlap with each other and other groups, the samples form two distinct clusters. Group CF3(WF3) contains samples, mainly from the lower diamicton at Site 1 except for sample F1.11 from the middle laminated diamicton unit also at Site 1, whilst group CF4(WF4) consists of samples mainly from the upper diamicton at Site 1. These two groups are almost identical to Facies 4 and 6, thus explaining the similarity of particle size ranges. Groups CF1 and CF2 (WF1 & WF2), which contain a number of samples from Site 1 and the majority of samples in Sites 2 and 3, have much larger ranges of particle size distribution. This is interesting, since the samples in this group were believed to be associated by all being of a coarser nature than samples in groups CF3(WF3) and CF4(WF4). Particle size analysis therefore shows that samples in these geochemical groups are not united by similar particle size distributions.

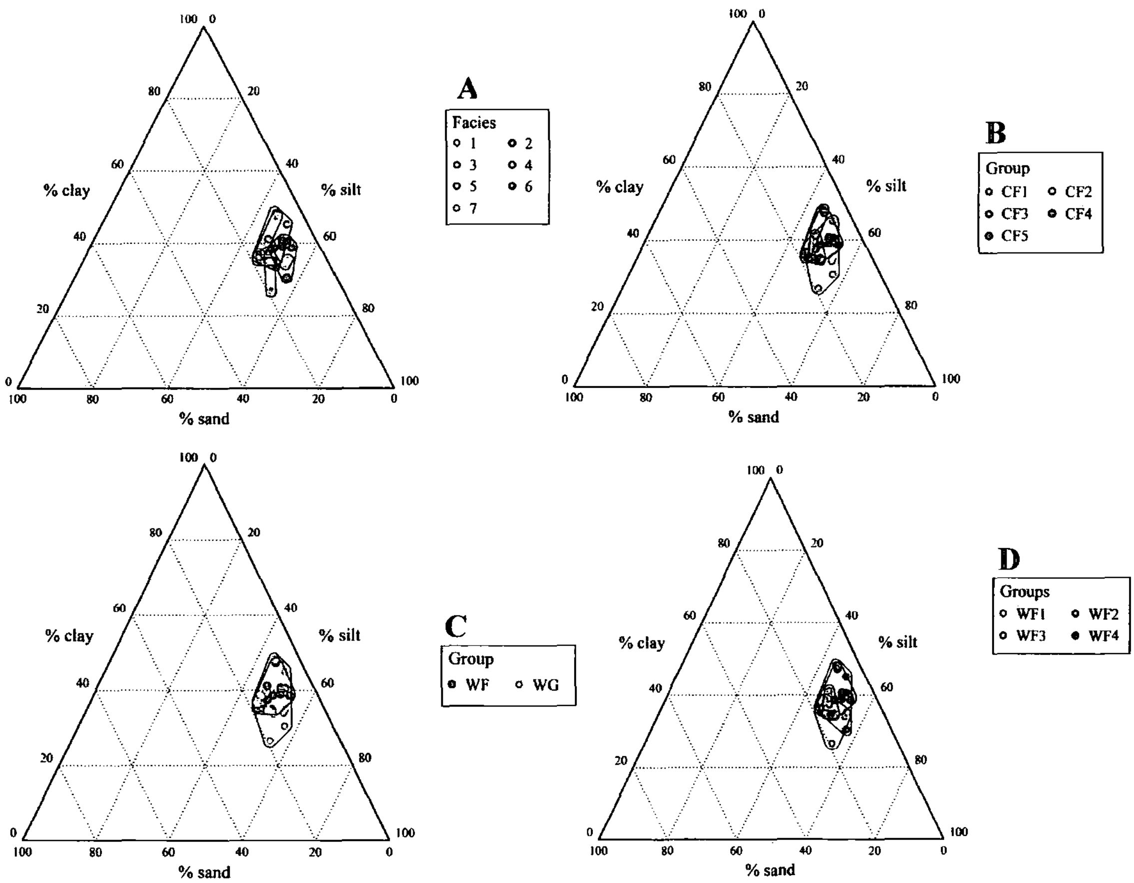


Figure 4.81. Particle size distributions of Filey samples by A) facies, B-D) geochemical group.

4.4.4 South Ferriby

Data from particle size analysis of samples at South Ferriby shows that the diamictons contain 36-51% clay, 39-49% silt, and 7-18% sand. Investigation of these particle size distributions with the diamicton units found at the two South Ferriby sites (Figure 4.82) reveals that there are significant differences in particle size between units. Facies 1 contains the basal diamicton at Sites 1 and 2, and the three samples taken from here consist of almost identical particle size distributions, which are shown in Figure 4.82 to be less silty than the majority of the other samples. The two samples taken from Facies 2 are much less similar in their particle size distributions, but are both predominantly less sandy than samples from other units, despite Facies 2 containing sand laminations. Samples from Facies 3, the upper diamicton at Sites 1 and 2, contain less clay than samples from Facies 1 and 2, and have a very similar particle size distribution to the sample SF2.4, taken from the weathered diamicton unit which caps the section at Site 2 (Facies 4).

Analysis of the relationship between particle size distribution and geochemical groups (Figure 4.82) demonstrates that there is a less significant relationship between the two, than between particle size and the diamicton units at South Ferriby. Both geochemical groups CSF1(WSF1) and CSF2(WSF2) contain samples with a wide range of particle size distributions, whilst group CSF4 has a very similar particle size distribution to a number of those in group CSF1.

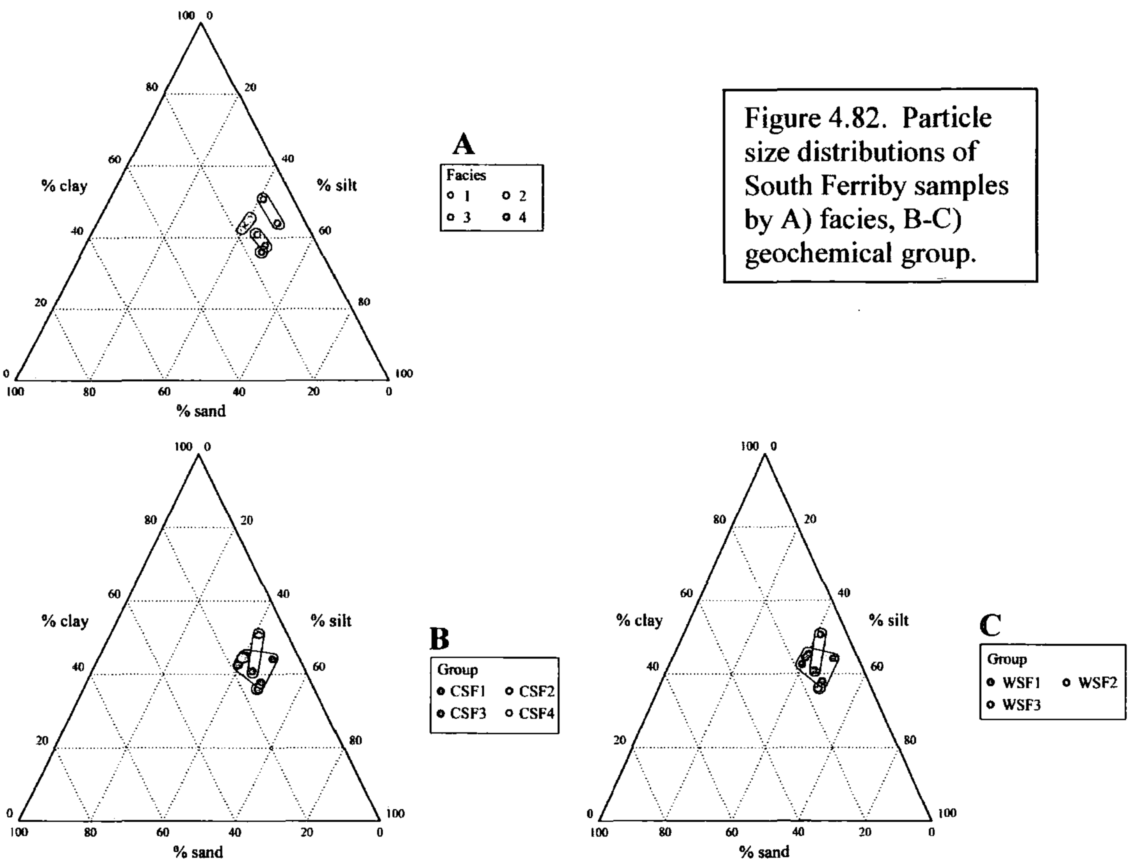


Figure 4.82. Particle size distributions of South Ferriby samples by A) facies, B-C) geochemical group.

4.4.5 Kirmington

Particle size analysis results from Kirmington show that the diamicton contains 32-43% clay, 45-50% silt, and 9-19% sand, where percentages of clay decrease upwards in the section, and proportions of silt increase. Figure 4.83 shows a significant difference in particle size between the two samples taken from Facies 1 towards the base of the section, and the sample taken from the upper weathered diamicton (Facies 2). Geochemical analysis of the samples revealed them to be relatively similar, although both the complete linkage and Ward's methods using combined z-scores do show that the weathered sample is the least similar of the three, therefore agreeing with the particle size results.

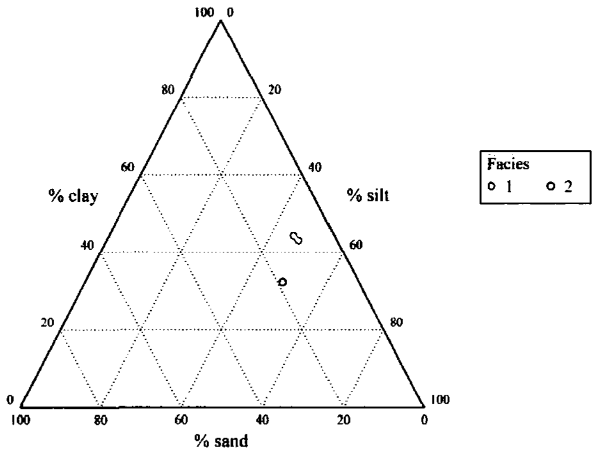


Figure 4.83. Particle size distributions of Kirmington samples by facies.

4.4.6 Welton-Le-Wold

Diamicton within the section at Welton-Le-Wold consists of 38-49% clay, 43-48% silt, and 8-15% sand, where the proportion of clay increases upwards in the section. The section is divided into three units, where Facies 1 represents the dark diamicton at the base of the section, Facies 2, represents the main body of diamicton in the section, and the upper weathered unit of diamicton is named as Facies 3. Division of particle size distributions into these facies (Figure 4.84) reveals that Unit 1 is very similar to Facies 2, whilst the sample taken from Facies 3 contains a much higher proportion of clay than the other samples. The limited number of samples taken at Welton-Le Wold, and analysed for particle size, means that any investigation of the relationship between particle size and geochemistry at this location is restricted. However, the results do show that there is unlikely to be a significant relationship between the two (Figure 4.84).

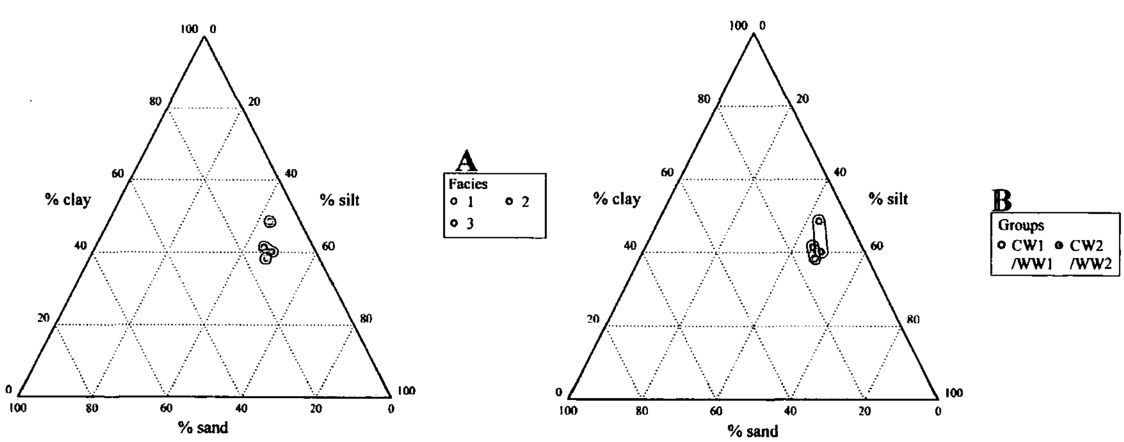
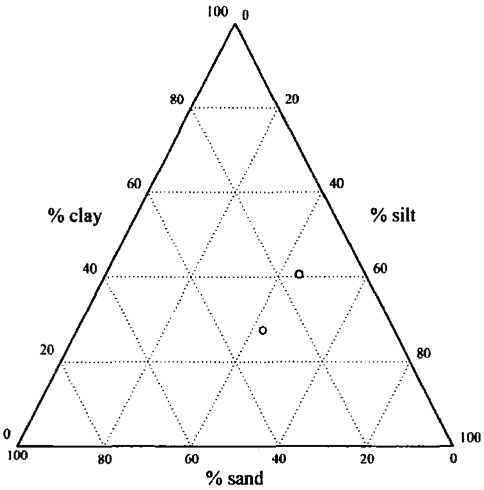


Figure 4.84 Particle size distributions of Welton-Le-Wold samples by A) facies, B) geochemical group.

4.4.7 Morston

Particle size distributions at Morston vary greatly between the upper and lower units, both of which are weathered, but the upper also shows evidence for re-working (Gale *et al.* 1986). Proportions of clay, in the two samples taken, vary between 27 and 41%, silt between 42 and 45% and sand between 14 and 30%. These results are displayed in Figure 4.85, which shows that the lower diamicton (Facies 1) at Morston is significantly lower in clay, and higher in sand, than the upper diamicton (Facies 2). Geochemical analysis however, shows that the matrix composition of the two samples is very similar, therefore displaying no relationship to particle size distributions at this site.



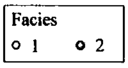


Figure 4.85. Particle size distributions of Morston samples by facies.

4.4.8 Comparison of Particle Size Distributions

The comparison of particle size distributions of the diamicton samples at each location is again hindered by potential differences in the results due to changes in water temperature (*cf.* Section 3.5.2). However, some useful deductions can be made (Figure 4.86). Evaluation of the three main locations shows that, in general, samples from Dimlington are less sandy, and contain a higher proportion of clay than those at Skipsea, whilst samples at Filey are generally more silty and less clay-rich than those at Dimlington. Figure 4.86 also demonstrates that samples from South Ferriby are richer in clay and less silty than those at Welton-Le-Wold and Filey, whilst the two unweathered samples from Kirmington contain particle size distributions which are similar to South Ferriby in terms of clay content, and similar to Welton-le-Wold in silt content. Particle size ranges at each location form relatively distinct groups, although there is significant overlap between them. This, in addition, highlights the large difference between the two particle size distributions at Morston.

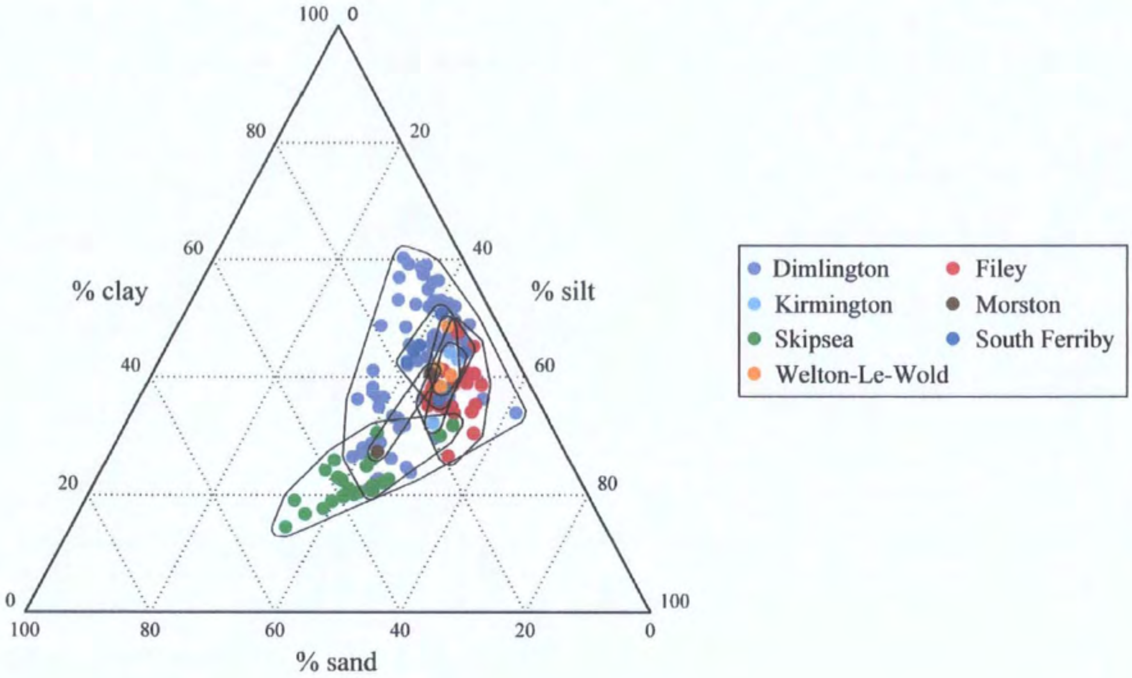


Figure 4.86. Particle size distributions of all samples by location.

Chapter 5: Interpretation

5.1 Introduction

This chapter examines the sedimentology and corresponding facies associations at each site. Interpretations are used to provide a context for the geochemical and particle size signatures found at each site and therefore, although they are based upon the sedimentary structures found within each facies, they generally follow current thought within previous literature, regarding depositional environments and ice dynamics. Interpretation is divided by site and at more complex sites the overall site interpretation is provided under the sub-heading 'Overview'.

5.2 Dimlington

Sediments at Dimlington are interpreted as a deformed sequence of tills with intervening stratified sediments. Reference is made to the traditional till units and whilst these can often be identified at the Dimlington sites based upon colour, geochemical analysis of the till matrix within these units is unable to differentiate the Basement, Skipsea and Withernsea till types.

Facies 1 consists of a massive, chalk rich diamicton of which the matrix colour varies between Munsell colour 10YR 4/1, 10YR 3/2, and 10YR 4/2. These colours are comparable with that assigned to the Skipsea Till (10YR 3/2) by Madgett & Catt (1978). The nature of the diamicton is also similar to the basal chalk-rich unit of the Skipsea Till described by Berridge and Pattison (1994), and Bisat's 'Division 1' (Drab 1) of the Drab (Skipsea) Till (Catt & Madgett, 1981) (Figure 5.1), in which he describes a lower chalk-poor diamicton beneath an upper chalk-rich unit, as at Site 2.

The massive nature of the diamicton could suggest deposition within a subglacial environment in which high incremental strain caused the homogenisation of the diamicton by repeated folding and attenuation episodes (Hart *et al.*, 1990; Hart & Boulton, 1991; Boulton, 1996a). Alternatively, Hart and Roberts (1994) suggest that deposition from suspension within the distal zone of a glaciomarine environment can produce structurally and lithologically homogeneous diamictons. However, the inclusion of bodies of lighter, chalk-rich material within the dark, chalk-rich diamicton, at Site 3, suggests incorporation of the chalk bedrock and incomplete mixing within a subglacial environment (Eyles *et al.*, 1994; Evans *et al.*, 2006).

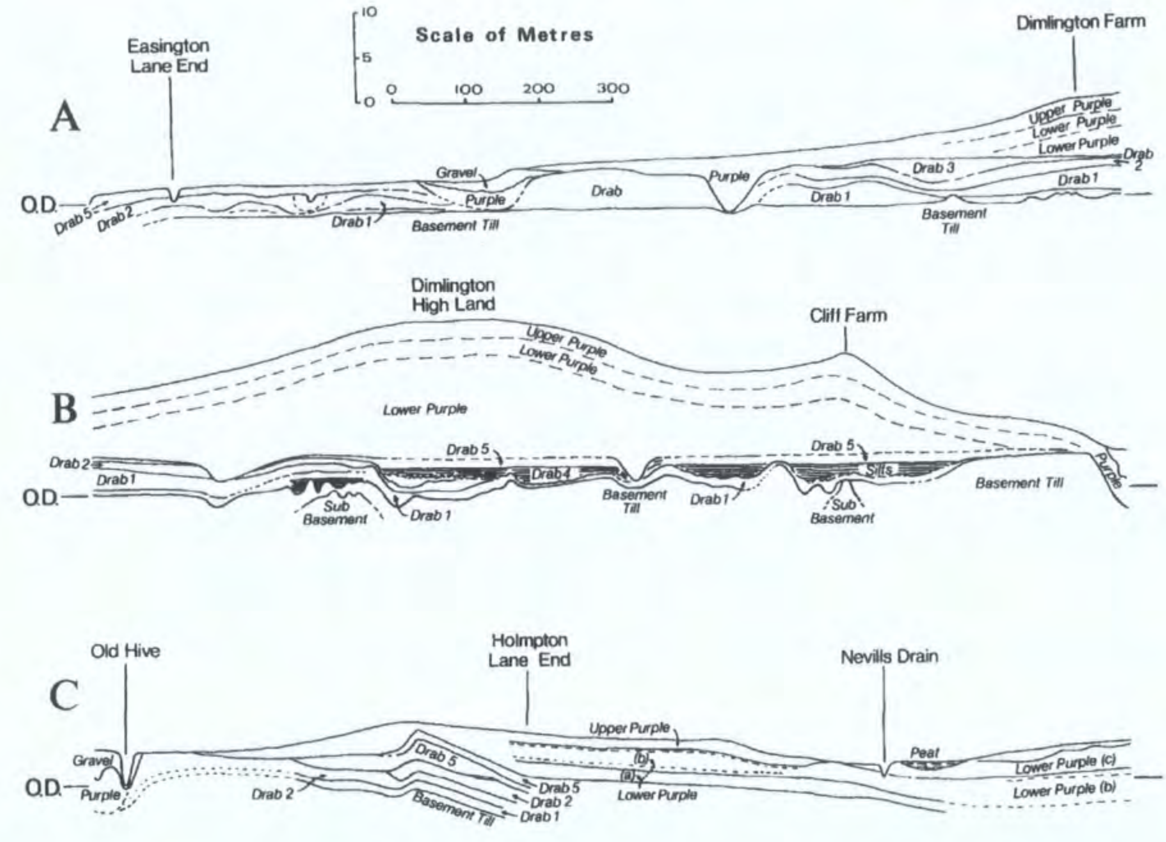


Figure 5.1. Section logs by Bisat, drawn mainly in the 1930's. A-C: Easington Lane End to Nevills Drain. Catt and Madgett, 1981, p.124.

Distinct layers of diffusely laminated diamicton occur above Facies 1, with each layer possessing slightly different matrix colours. The layers are comparable to the thin beds found within Bisat's Division 2 (Drab 2) of the Skipsea Till (Catt & Madgett, 1981) (Figure 5.1). The laminations are extensively folded at Sites 4 and 7, and at other places along the Dimlington cliffs (see Figure 4.2), which implies that this unit has been subject to compressional glacitectonism (Benn & Evans, 1998; McCarroll & Rijsdijk, 2003). It is less clear, however, whether the sediments were laid down proglacially and subsequently overridden and deformed by the ice sheet (Hart & Roberts, 1994; Roberts & Hart, 2005), or whether the laminations represent the incorporation of local material into the subglacial traction layer, and limited exposure to a number of folding events (Boulton, 1996a).

The sequence above Facies 2, towards the top of the Site 2, 3 and 4 sections comprises of a massive diamicton grading upwards into laminated clays, which in turn coarsen upwards into laminated sands. The laminated beds are interpreted as a proglacial lake sequence. The gradational contact of the laminated clays with the underlying diamicton suggests that the latter was deposited subaqueously as a mass flow (Hart & Roberts, 1994; Evans & Ó Cofaigh, 2003). Contorted gravel pendant structures, found sporadically between the diamicton and laminated clays at Site 2, reflect a vertical, gravity-driven deformation style (McCarrol & Rijsdijk, 2003). Where high-density gravels are deposited over lower density muds and diamictons, Rijsdijk (2001) argues that density-driven deformation will occur if the sediments are able to behave in a viscous manner. This will occur when water content within the sediment is high and shear strength is low. These gravel features therefore support a subaqueous genesis for the diamicton unit rather than a compact subglacial till (Hiemstra *et al.*, 2005).

The occurrence of this waterlain diamicton on top of subglacially derived diamictons records a transition from a subglacial to an ice-marginal environment, the upward transition from the predominantly massive diamicton into laminated clays indicating a switch to a lower energy environment and the settling of fine suspended sediments. The gradual coarsening of the sediments upwards into sand through alternate clay and sand laminae, additionally reflects changes in flow regime and the horizontal bedding of the sands suggests that they were deposited on either a flat stream bed or in shallow water flowing over a sandur (Church & Gilbert, 1975; Shaw, 1975).

Where the upper surface of the sand unit is visible, it displays a sharp contact with the diamicton above, suggesting that the ice margin readvanced over the stratified sediments. Overriding of the sand unit by this subsequent ice advance appears to have caused little or no deformation in the underlying unit. Evans *et al.* (2006) suggest that sand-rich sediments possess a greater frictional strength than clay-rich lithologies, and as a result are more resistant to deformation. Sand-rich sediments are also more efficient at draining meltwater, which leads to lower pore water pressures and prevents deformation (Boulton, 1996a). Therefore, despite proposals that deeper deformation is caused by greater ice-bed friction as glaciers move over sand lithologies compared to clay (Boulton *et al.*, 2001; Piotrowski *et al.*, 2004), it is conceivable that the sand bodies at Dimlington lack clear signs of deformation due to their greater cohesive strength. The sand unit is up to 4m thick and may have acted as a buffer, preventing deformation in the clay sediments below; few experiments have observed deformation occurring at depths of more than 1m (*cf.* Truffer *et al.*, 2000) (Boulton *et al.*, 2001). Lenses of contorted and attenuated clay, silt, sand and gravel within the upper, red-brown diamicton (Facies 11) at Site 10 suggest that the contact between the stratified sediments and overlying diamicton is deformational, providing evidence for the excavation of pods of material from the underlying sediment (Eyles *et al.*, 1994; Roberts & Hart, 2005). This is supported by the occurrence of sand units in elevated positions at other places along the cliff.

In most parts of the cliff where the stratified sediment bodies occur, they are observed to rest entirely between the lower dark grey-brown and upper dark brown diamictons, which are likely to be equivalent to the Skipsea and Withernsea tills. Site 8, however, presents a more complicated succession (see Figure 4.17). Here dark, grey-brown diamicton is found to also lie above the laminated clay and sand unit, which is much thinner than at other sites (2m in total). The upper half of the diamicton appears browner and is separated from the darker diamicton below by pale and red diamicton bands. This upper diamicton lies below beds of horizontal and planar cross-bedded gravels, before the main body of dark brown diamicton begins. In addition, Berridge and Pattison (1994) recorded laminated silts above the sand unit, where the boundary between the two units was less sharp, and continuous sand laminations occurred in the basal layers of the silt unit (Figure 5.2). Furthermore, Eyles *et al.* (1994) found Withernsea Till below the southern part of the sand and clay unit (Figure 5.3). The interdigitating occurrence of clays, sands, gravels and silts with the diamicton units, implies that the ice margin oscillated into the proglacial lake on at least one occasion before a further readvance. This may explain the changing position of the sand and clay bodies within the diamictons over time (Bisat in Catt & Madgett, 1981; Catt & Penny, 1966; Berridge & Pattison, 1994; Eyles *et al.*, 1994) (Figures 5.1-5.3), where the evidence for temporally and spatially distinct ice-margin oscillations is revealed in the cliff face at any one time due to cliff erosion.

Distinction between the traditional Skipsea and Withernsea tills is made at Site 5 based upon colour, where a sharp contact separates a dark grey-brown (10YR 3/2) diamicton (Facies 5) from a dark brown (10YR 4/3) diamicton (Facies 6) at 4.5m above the beach. These colours provide a close match to the traditional Skipsea (10YR 3/2) and

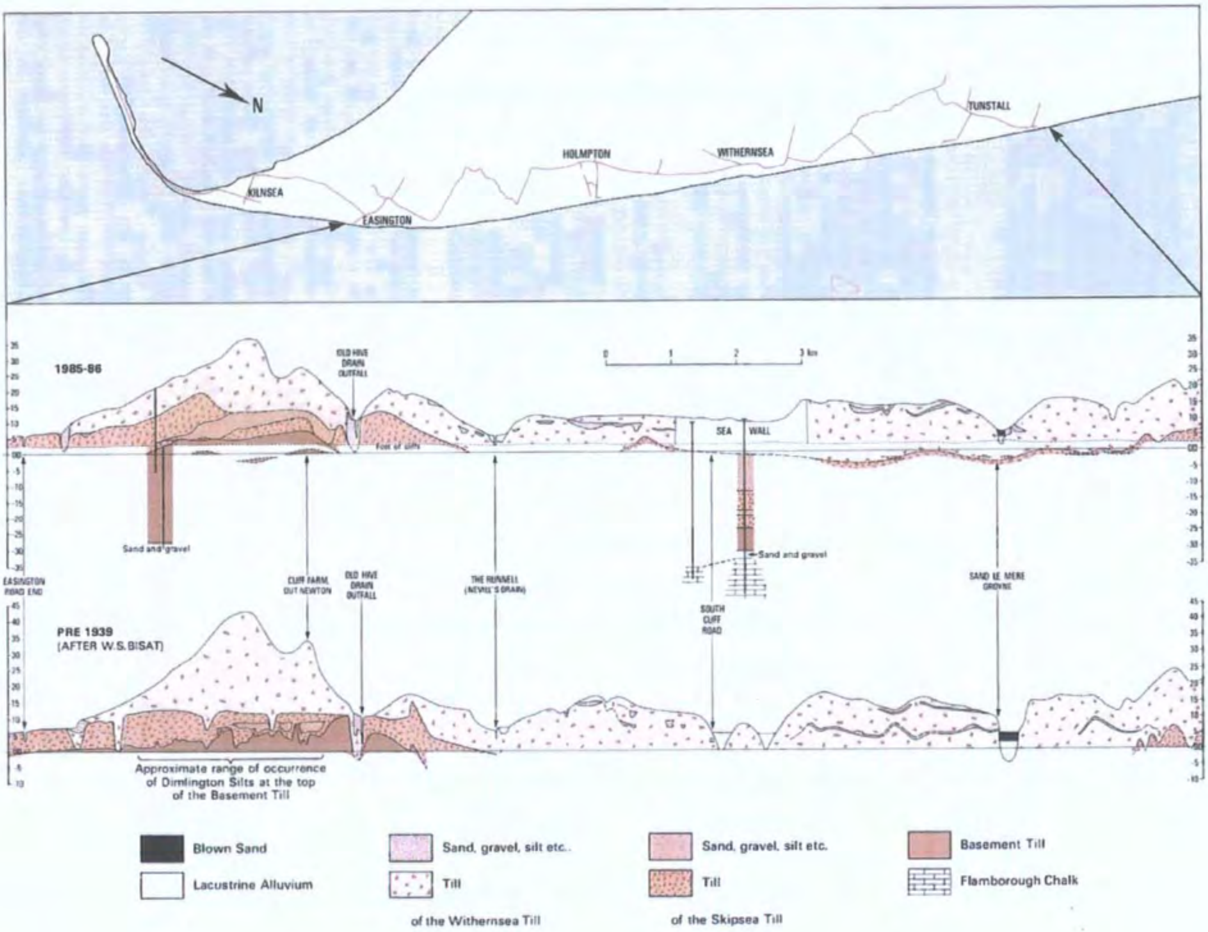


Figure 5.2. Till stratigraphy in cliff sections from Easington to Tunstall, including observations by Bisat. Berridge and Patterson, 1994, p.47.

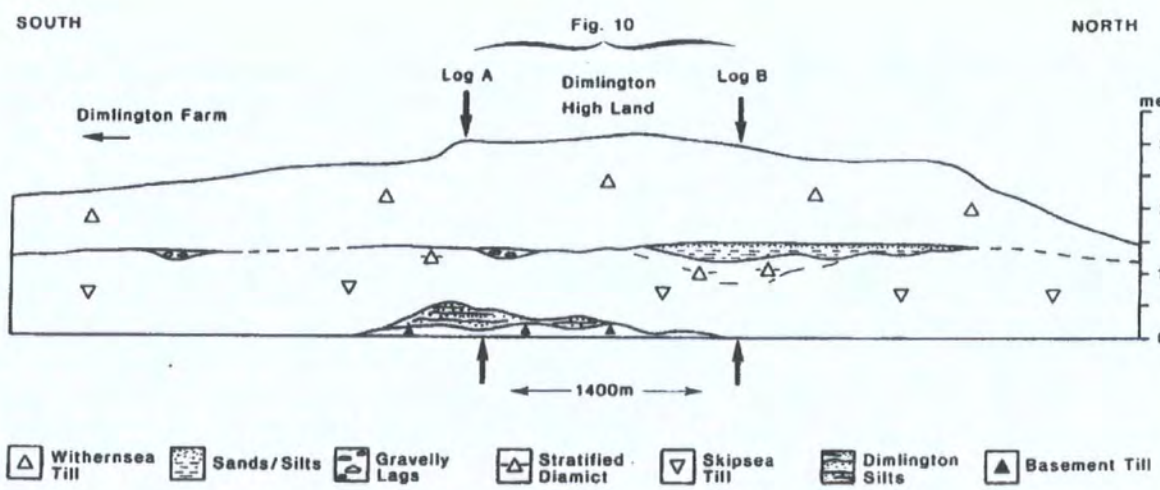


Figure 5.3. Section log from cliff exposures at Dimlington. Eyles *et al.*, 1994, p.733.

Withernsea (7.5YR 3/2) till colours, and therefore support an argument that Facies 5 can be assigned to the Skipsea Till, and Facies 6 can be classified as the Withernsea Till. However, a less distinct difference is observed in both the particle size and geochemical results. Particle size differences between Facies 5 and Facies 6 show a wide range of particle size distributions within each unit, and a large overlap between the two (see Figure 4.79). Geochemical analysis shows no difference between Facies 5 and Facies 6 at this site, where samples taken below and above the boundary exhibit very similar abundances of elements (see Figures 4.42, 4.43, 4.48 and 4.49), strengthening an argument for the similarity in geochemical composition of the Skipsea and Withernsea Tills.

The absence of stratified sediment (Facies 4) between the Facies 5 (=Skipsea Till) and Facies 6 (=Withernsea Till) at this site suggests that either the ice sheet oscillations were very local or, that the stratified unit was removed in this area by the ice readvance that deposited the Withernsea Till. The occurrence of a thin (0.3-0.5m thick) sand and gravel unit within the basal layers of the Withernsea Till could either be due to the cannibalisation of pre-existing sediments (i.e. from the absent stratified sediment unit) (Evans *et al.*, 2006), record subglacial drainage channels (Alley, 1992; Clark & Walder, 1994) (see Section 2.5), or be deposited by subglacial meltwater sheetflow during periods of ice-bed separation and glacier sliding (Piotrowski *et al.*, 2001, 2002). The unit displays some evidence of deformation, especially within the clay horizon. However the recognisable nature of the original bedding structures and near horizontal orientation of the bed suggests *in situ* deposition by meltwater drainage and subsequent deformation (Evans *et al.*, 1995; Boyce & Eyles, 2000), rather than the cannibalisation and rafting of the sediments into this position.

The colour and structure of Facies 7 (=Withernsea Till) remains fairly consistent vertically throughout its exposure, apart from some lightening in places due moisture variability. At close distance the diamicton appears massive, but from further away laminations are identified as subtle changes in colour of the diamicton matrix. The only exception to the continuity is at Site 5C, where bands of lighter and darker till, 0.2-0.5m thick occur, which also exhibit variations in chalk clast content. Geochemistry results from this section show that there are significant changes in the proportions of a number of elements in this section, where till samples, less than 0.5m apart vertically, contain very different element concentrations. Areas of geochemically similar sediments alternate and are repeated upwards in the whole of the sequence between 5 and 14m above the beach, suggesting that folding and stacking of rafts of sediment has occurred in this section. No deformation structures are found in this area, and apart from the limited amount of banding at Site 5C, the diamicton appears structurally macroscopically homogenous. Evans *et al.* (2006) suggest that in the absence of preferential weathering, till may appear massive, despite containing fine, texturally distinct laminations. It may therefore be conceivable that the till in this section does contain laminations that could display extensive folding, but due to the position of the section, away from intense weathering from wave action, any signs of deformation are not visible in the field.

The upper diamicton units at Sites 5 and 1 (Facies 8) display a number of characteristics attributable to weathering. Firstly, the colour lightens and reddens to Munsell Colours between 7.5YR 4/3 and 7.5YR 6/3. A reddening of the till matrix occurs due to the mobilisation of iron oxides and hydroxides from the weathering of heavy minerals such as pyrite, siderite, chlorite and chamosite (Madgett & Catt, 1978). Calcium is also a highly mobile element, where Ca^{2+} readily dissolves into acidic solution and is leached out (Burek & Cubitt, 1991; Albarède, 2003). The absence of chalk clasts within the diamicton at Sites 1 and 5D, as well as the limited amount of limestone clasts compared to the unweathered diamicton immediately below it, suggests that significant weathering has occurred in this section. Facies 8 is therefore comparable to the previously known Hessle Till, which has subsequently been demonstrated to be a weathered part of the Withernsea Till (Madgett & Catt, 1978).

Geochemical analysis demonstrates that Facies 8 is most similar to Facies 9 at Site 6 and the dark, chalk-poor diamictons (Facies 2), classified within the Skipsea Till unit at Sites 2, 3, and 4. As discussed in Section 4.3.1, clustering of these very distinct units may have occurred due to their low abundances of calcium. Figure 5.4 shows that at Site 5, abundances of Ca and Sr are lower in the basal diamicton (Facies 5 and 6) and upper weathered diamicton (Facies 8), compared to higher abundances the middle section of the cliff (Facies 7). However, Figure 5.4 also demonstrates that Facies 5, 6 and 8 also contain similar abundances of Ti, Fe, Al and Rb, which are significantly different to Facies 7. In addition, Figure 5.5 demonstrates that whilst calcium contents are low in the lower dark tills (Facies 2) and weathered upper tills (Facies 8) they are not identical. Other elements such as K, Ti, Fe, Mo, Sn, Rb, Pb and U are more significant in clustering these groups of diamictons together. This geochemical similarity between diamicton at the top and the bottom of the sequence supports evidence in Facies 7 for the stacking of sediments from lower down and the incorporation of pre-existing material.

The dark grey lower diamicton (Facies 9) at Site 6 possesses a Munsell colour of 10YR 4/1. Although this is not identical to the Munsell colours ascribed to the Basement Till of 5Y 3/1 to 5Y 4/2 in previous work (Madgett & Catt, 1978), the colours are similar. The unit also displays other characteristics that liken it to the traditional description of the Basement Till (*cf.* Catt & Penny, 1966; Madgett & Catt, 1978, Catt, 2007), such as a low proportion of chalk clasts. Despite particle size distributions not lying within the Basement Till particle size range defined by Catt (2007), possibly due to differences in particle size analysis methods, they do contain less silt than the majority of samples from Dimlington, as well as consisting of high proportions of clay. These characteristics are compatible with textural results for the Basement Till from Madgett & Catt (1978). As discussed in Section 4.3.1, particle size distributions from Facies 9 are very distinct from those in the dark brown diamicton above (Facies 10), thus supporting the assertion that Facies 9 is Basement Till.

Interestingly, results from the geochemical analysis show that sample D6.3, taken from the upper layers of Facies 9, is geochemically more similar to samples taken from Facies 10 than other samples taken from Facies 9. This indicates that the upper layers of the Basement Till represent a zone of mixing following glacial overriding and the deposition of Facies 10. Ring shear experiments (Hooyer & Iverson, 2000), have shown that shear strain at the glacier bed causes the mixing of tills across boundaries, despite these boundaries often appearing sharp at macroscale (Boulton *et al.*, 2001; Piotrowski *et al.*, 2001, 2002).

Assignment of Facies 9 to the Basement Till implies that the diamicton above it (Facies 10) is Skipsea Till. The colour of this diamicton, 10YR 3/2 matches the colour recorded by Madgett and Catt (1978) for the Skipsea Till. Particle size distributions from this unit show that compared to samples from higher parts of the cliff (Facies 7 and 8), the unit is sandier, and therefore is also compatible with a Skipsea Till classification. Geochemical analysis clusters this Facies 9 with the diamictons both above and below

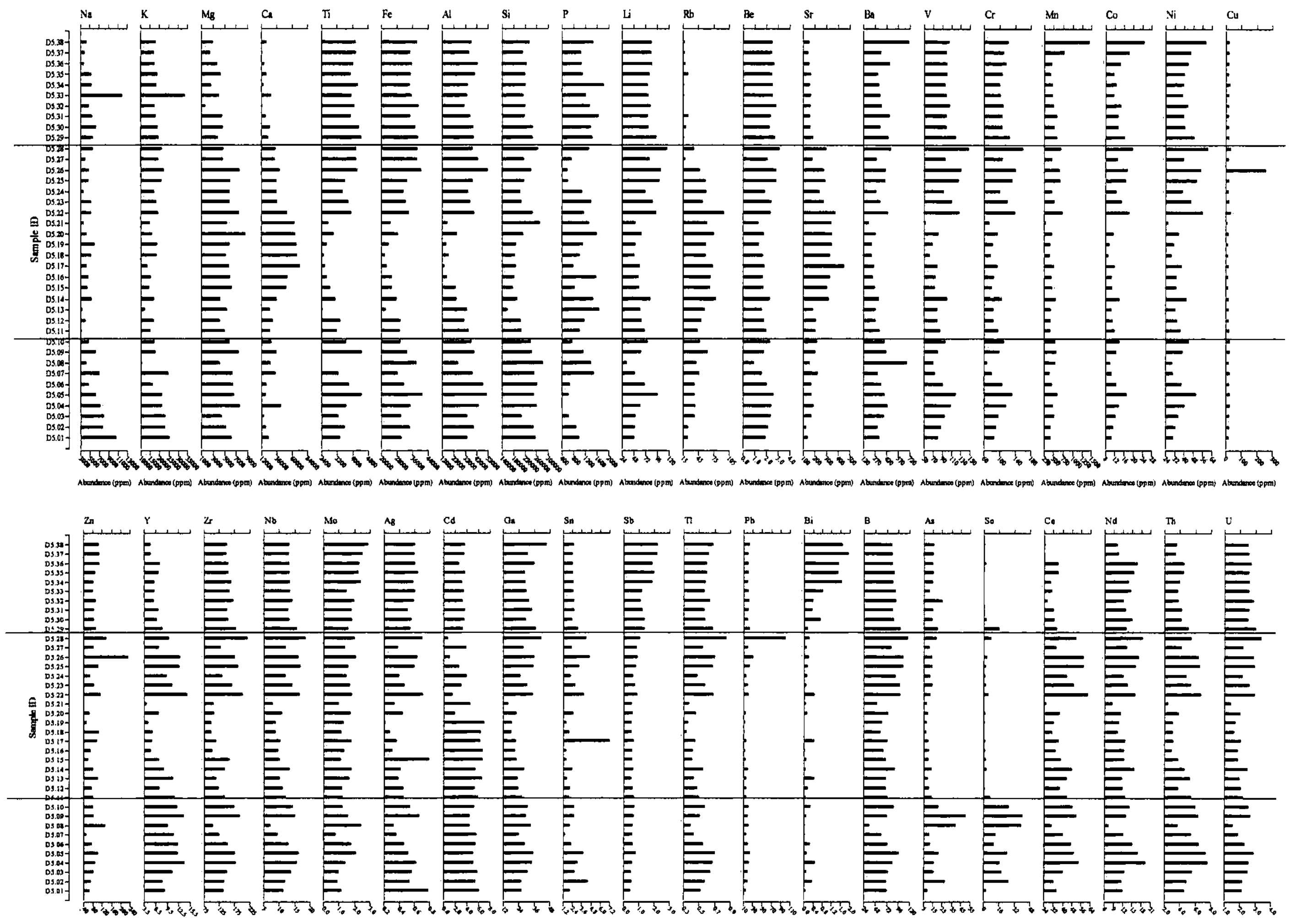


Figure 5.4. Element abundances in samples from Site 5 Dimlington by sample. The graphs are divided into three sections to highlight the lower (Facies5 and 6), middle (Facies 7) and upper (Facies 8) parts of the section.

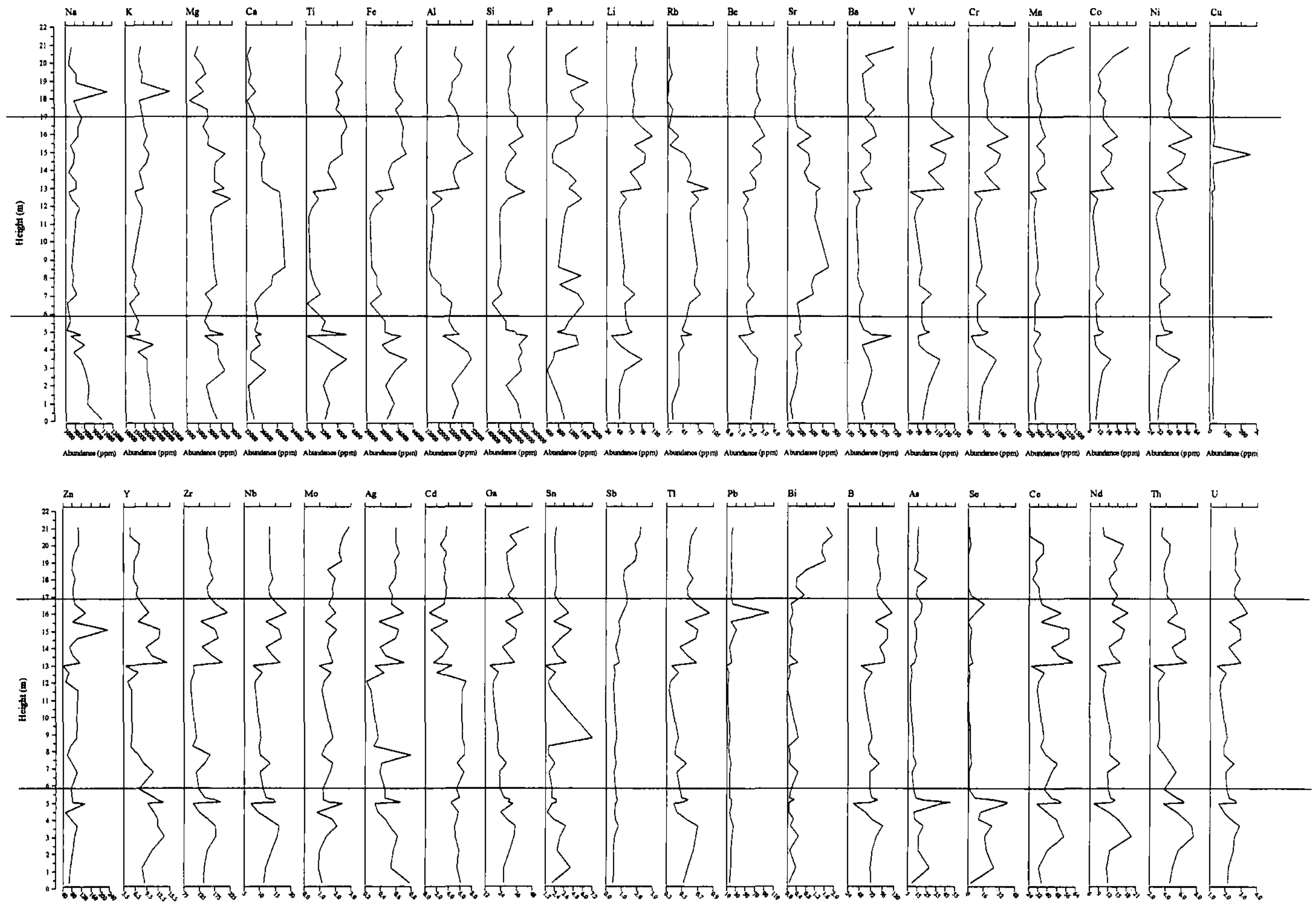


Figure 5.4 *continued.* Element abundances in samples from Site 5 Dimlington by height. The graphs are divided into three sections to highlight the lower (Facies5 and 6), middle (Facies 7) and upper (Facies 8) parts of the section.

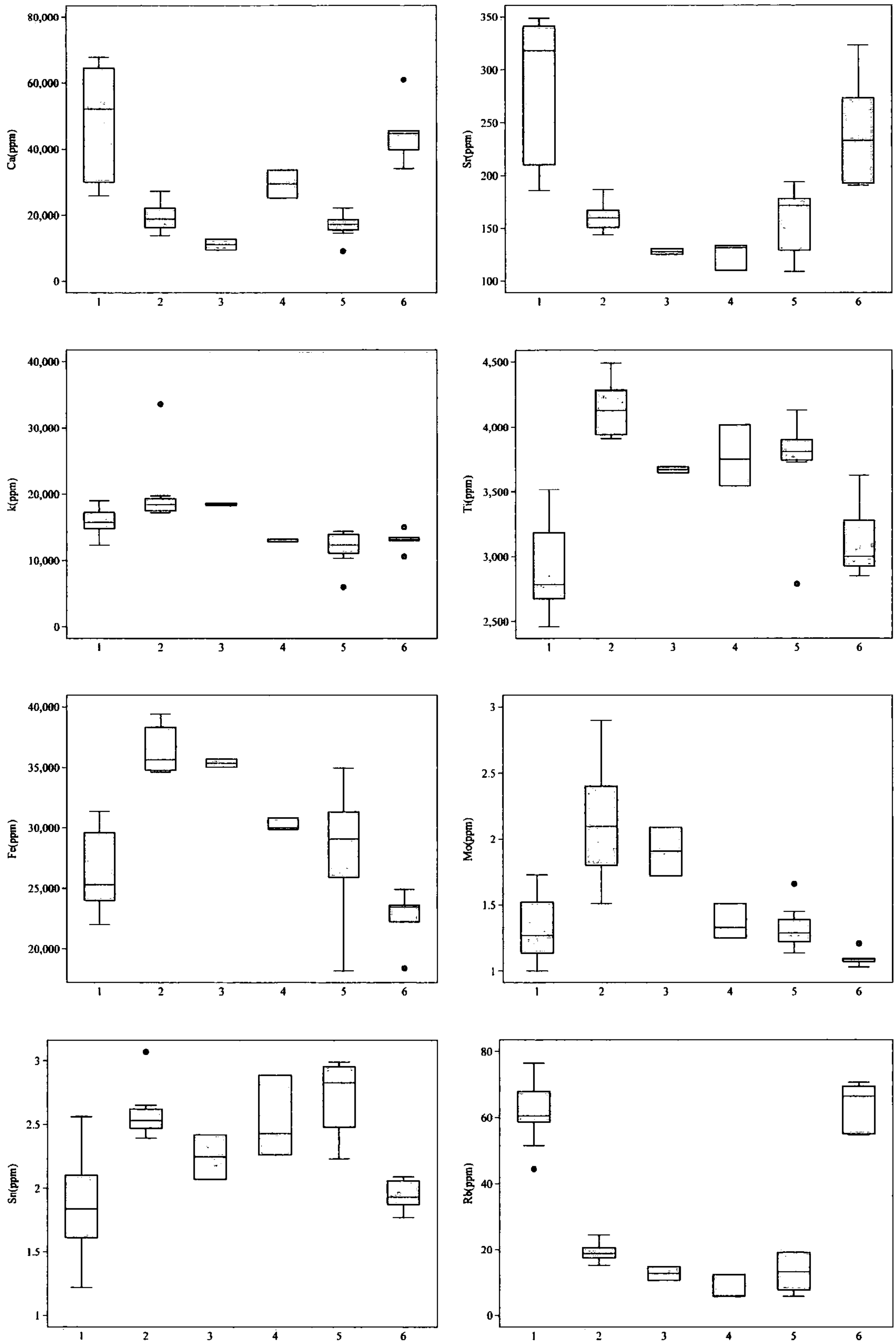


Figure 5.5. Element abundances of particular groups of diamictons at Dimlington, where Group1 = samples from Facies 7, Group 2 = Facies 8 Site 5, Group 3 = Facies 9, Group 4 = Facies 8 Site 1, Group 5 = samples from Facies 2, and Group 6 = Facies 1.

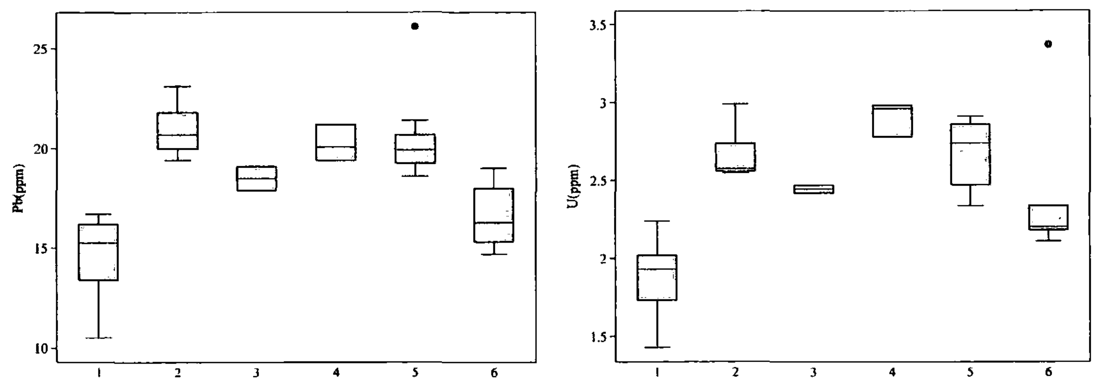


Figure 5.5 *continued.*

the sand unit at Site 10 (Facies 2, 3 and 11). The browner colour of the upper diamicton (Facies 11), compared to the lower diamictons at Site 10, and its location above the stratified sediment unit (Facies 4), identify it as Withernsea Till. Particle size analysis also demonstrates that it contains less sand, and more clay than that of the lower diamictons. However, its colour when wet is 10YR 3/2, the same as the Skipsea Till (Madgett and Catt, 1978). The geochemical similarity of diamictons at Sites 6 and 10 therefore suggests that at these sites, the Withernsea Till possesses some similarities to the Skipsea Till.

Overview

Figures 4.42, 4.43, 4.48 and 4.49 show that geochemical signatures within the tills at Dimlington, particularly in the succession at Site 5 (Facies 5, 6, 7 and 8), are repeated upwards throughout the exposure. This suggests that the tills at Dimlington may have been deposited through the folding, attenuation and stacking of layers of material as a result of glacitectonic transposition (van der Wateren, 1995). Eyles *et al.* (1994, p.749) describe "discontinuous frontal ridges along the western margin of the Withernsea Till" which decline into hummocky topography containing further discontinuous and cross-cutting ridges, and disconnected mounds. Although Eyles *et al.* (1994) use this geomorphological evidence to support a model for surging, this geomorphological signature could also suggest the production of a glacitectonically folded and thrust push moraine (Aber *et al.*, 1989; van der Wateren, 1995, 2003) at this site. This is supported by the raised land surface at Dimlington High Land, beneath which Site 5 is situated. Van der Wateren (1995) suggests that where a push moraine is mainly made up of fine-grained sediments, the tectonic style is predominantly ductile, producing structures such as folds and fold nappes. Sediments at Dimlington are predominantly composed of fine-grained sediments and the sedimentological signature supports folding rather than thrusting as a means of producing the geochemical signal found, since the till appears macroscopically homogenous in most places. The tectonic style at Dimlington is therefore likely to be most similar to the Holströmbreen model from Spitsbergen (Boulton *et al.*, 1989; van der Wateren, 1995), where folding is dominant and consists of concentric folds, fold-thrust nappes and gravitational nappes. Any cannibalisation and tectonic stacking of pre-deposited material to produce this push moraine invokes the inference that there should be a source depression located up glacier, beneath the present North Sea (Aber *et al.*, 1989; van der Wateren 1995; Boulton 1996a, b), which requires further investigation.

A model is proposed for the deposition of the sediments at Dimlington based upon the sedimentological and geochemical results of this research (Figure 5.6). Southwards advance of the Late Devensian North Sea ice lobe along the east coast of England caused localised ponding on the surface of pre-existing glacial deposits (=Basement Till) and the deposition of stratified sediments (=Dimlington Silts). Eyles *et al.* (1994) suggest that tidal currents influenced the sedimentation of these silts but the evidence for this is equivocal. During the subsequent onshore advance of this ice sheet, in the area of Holderness, the upper layers of the Basement Till and Dimlington Silts became cannibalised and incorporated into the active till layer (=Skipsea Till) (Hart & Boulton, 1991; Eyles *et al.*, 1994; Evans *et al.*, 2006). This explains the occurrence of a lower dark grey, chalk-poor till at the base of the Skipsea Till unit (*cf.* Madgett & Catt, 1981) found at Site 2 and it is reflected by the similar geochemical signature across the boundary between the traditional Basement and Skipsea tills at Site 6. Continued excavation of pre-existing material and subsequent quarrying of the chalk bedrock sourced the dark chalk-rich unit (Facies 1) of till found at Sites 2 and 3, and therefore the upper layers of Facies 1 are likely to contain a more local geochemical signature than the lower layers deposited directly above the Basement Till or Dimlington Silts. This is reflected in the differences found in the geochemistry of Facies 1 at Site 2 and Facies 10 at Site 6.

Hart and Boulton (1991) propose that as time progresses, both local and far travelled material begin to be deposited, which causes the pre-existing material to become sheared out. The later incorporation of more far travelled material may explain the

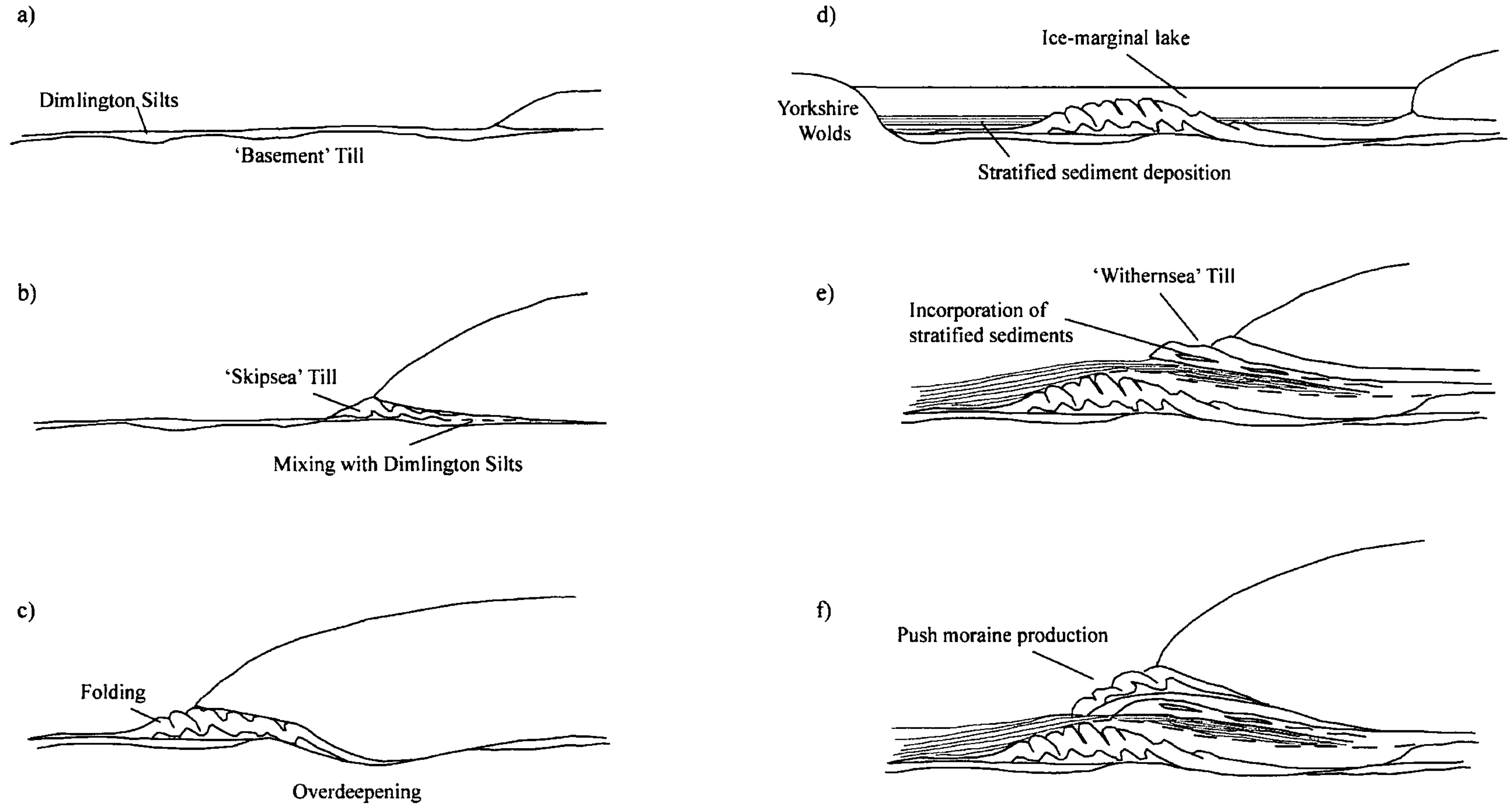


Figure 5.6. Schematic model of North Sea ice lobe dynamics and till deposition, with reference to the traditional till units. a) Initial ice advance over the 'Basement' Till, created ponding and the deposition of the Dimlington Silts. b) Incorporation of the Dimlington Silts into the subglacial traction layer and mixing with more distal sediments. c) Compression and folding of the 'Skipsea' Till at the ice margin and overdeepening in the sub-marginal zone. d) Ice margin retreat across Holderness. Damming of the Humber Gap by ice in the North Sea created Glacial Lake 'Holderness' and caused the deposition of stratified sediments across the region (*c.f.* Thomson & Evans, 2001). e) Overriding of the stratified sediments by ice readvance of an oscillating margin and the cannibalisation of some stratified sediments into the 'Withernsea' Till. f) Production of a push moraine at Dimlington High Land during a major ice advance.

reduction in chalk in the higher units of the Skipsea Till (Facies 2), where the assemblage of elements becomes richer indicating that the till may contain a higher proportion of clasts from shales and mudstones further north compared to within Facies 1. Attenuation of pre-existing material may have produced the laminated nature of these units, caused by changes in grain size and subtle colour variations. The intense folds found in this unit indicate that compressional deformation occurred, and therefore record ice margin proximity during this time (McCarroll & Rijsdijk, 2003). Additionally, Boulton (1996a) proposes that the presence of folds within the till indicates that deposition occurred shortly after an initial folding event before homogenisation of the till occurred through numerous folding events.

Retreat of the ice margin left a proglacial lake in which a massive diamicton was deposited subaqueously (Hart & Roberts, 1994; Evans & Ó Cofaigh, 2003). Transition of this diamicton into laminated clay, reflects the continued retreat of the ice margin and the change to a low energy environment. Changes in the position of the stratified sediments within the different till units provides evidence for ice margin oscillations during this time. Sediments recording increasing ice proximity following the return of the North Sea ice lobe are lacking and may have been eroded and cannibalised as the glacier overrode the glacilacustrine sediments. Evidence for the erosion of rafts of material is found in the basal layers of the upper diamicton unit (Facies 11 =Withernsea Till) in the form of attenuated pods of sand, clay and gravel (Eyles *et al.*, 1994). As discussed above, geomorphological evidence of ridges in the surface of the Withernsea Till (Eyles *et al.*, 1994), such as the remarkably thick sequence of Withernsea Till forming the ridge at Dimlington High Land, combined with the repeated nature of the geochemical signature, is explained by the production of a glacitectonically folded and stacked moraine at Dimlington.

5.3 Skipsea

Sections at Skipsea reveal a laminated diamicton, which contains discontinuous intervening stratified sediments, and either grades into, or is separated by, a clast lag from an upper massive diamicton. Both diamictons are interpreted as subglacial deformation tills in which the stratified sediments represent a migrating drainage network (Boulton & Hindmarsh, 1987; Alley, 1991; Clark and Walder, 1994). Similarities are found with Bisat's two unit division of the till sequence at Skipsea and the stratified sediment basins found at the top of the succession. However, Bisat's descriptions of the Lower and Middle Drab Tills do not correlate exactly with the till characteristics found here (Catt & Madgett, 1981) (Figure 5.7).

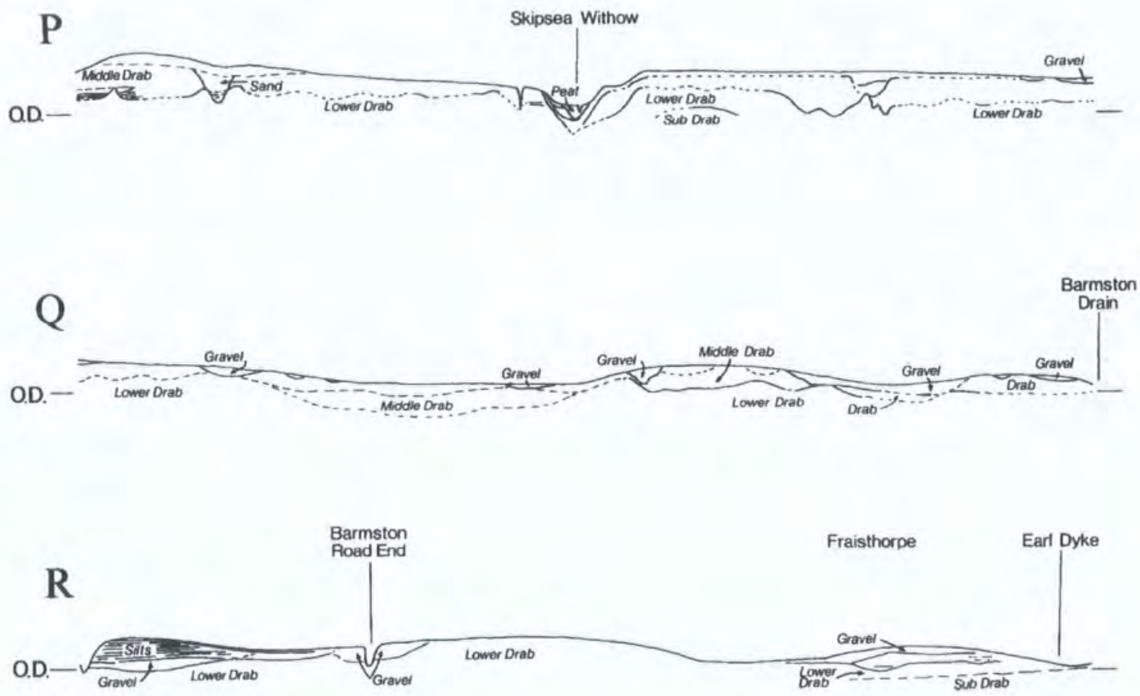


Figure 5.7. Section logs by Bisat, drawn mainly in the 1930's. P-R: Skipsea Withow to Earl Dyke. Catt and Madgett, 1981, p.129.

The laminae displayed within the lower diamictons (Facies 1) at Sites 1 and 3 are the product of subtle textural variations and are therefore only visible due to differential weathering. A number of authors (Roberts & Hart, 2005; Evans & Ó Cofaigh, 2003) propose that faint stratification due to discontinuous subparallel laminations can indicate deposition within a subaqueous environment. However, there is no evidence at Skipsea for deformation of the laminations around clasts (dropstones), whilst extensive evidence for folding and attenuation, such as the clay fold at Site 1, points to a subglacial origin of the diamicton (Boulton *et al.*, 2001). Roberts and Hart (2005) suggest that thin laminae ("Type 1") are produced by extensional glaciotectonism and intergranular shear mechanisms. Thin sand partings have also been proposed to record episodes of ice-bed separation and the drainage of basal meltwater, which have been subsequently attenuated by deformation of the active till layer (Piotrowski & Tulaczyk, 1999; Boyce

& Eyles, 2000; Evans & Ó Cofaigh, 2003). Alternatively, Roberts and Hart (2005) argue that continuous "Type 2" laminae form following the deformation of pre-existing stratified sediments. Both interpretations feasibly reflect the nature of the diamictons at Skipsea, where it is clear that attenuation and folding of the sediments has occurred. In addition, at Site 1, the transition of laminated diamicton upwards into massive diamicton (Facies 2) is also characteristic of deformation till sequences, where the transition reflects an increase in cumulative strain upwards in the section (Benn & Evans, 1996; Boulton, 1996a; Ó Cofaigh & Evans, 2001).

The shape of the sand cavity at Site 4 (Facies 4) is unlike the convex base and planar upper contact characteristics described by Evans *et al.* (1995) of cavity fills at Skipsea. Complex fold structures within the sand, particularly at the southern end, in addition to the sheared and loaded upper contact, indicate that the cavity fill has been subject to moderate deformation. Deformation of the cavity fill explains the difference in shape between this cavity and undeformed cavities described by Evans *et al.* (1995).

The deposition of stratified sediment bodies within basal till layers has invoked two main hypotheses to explain their occurrence. Firstly, meltwater drainage during melt-out till deposition has been proposed as a process for creating stratified lenses in glacial diamictons (e.g.Shaw, 1982; Munro-Stasiuk, 2000). Alternatively, the stratified sediments are believed to represent subglacial drainage channels and cavities, preserved during till accretion beneath active ice (Eyles *et al.*, 1982; Alley, 1991, 1992; Clark & Walder, 1994; Evans *et al.*, 1995; Boyce & Eyles, 2000). Following on from the assertion made above, that the diamictons at Skipsea reflect accretion of a subglacial deforming till layer and that they exhibit no evidence for a period of stagnation, it is most likely that the channel and cavity fills found at Skipsea were deposited during the accretion and deformation of till beneath active ice. Geochemical analysis supports this, revealing that the geochemical composition of the upper and lower diamictons (Facies 1 and 5) surrounding the cavity is very similar. Conversely, the diamicton bands within the cavity cluster separately from the rest of the diamicton samples at Skipsea, and exhibit a much higher abundance of silver (Ag) (see Figures 4.44, 4.45, 4.50 and 4.51). This implies that sediments injected into the cavity may have been subject to less mixing and homogenisation than sediments within the deforming till layer.

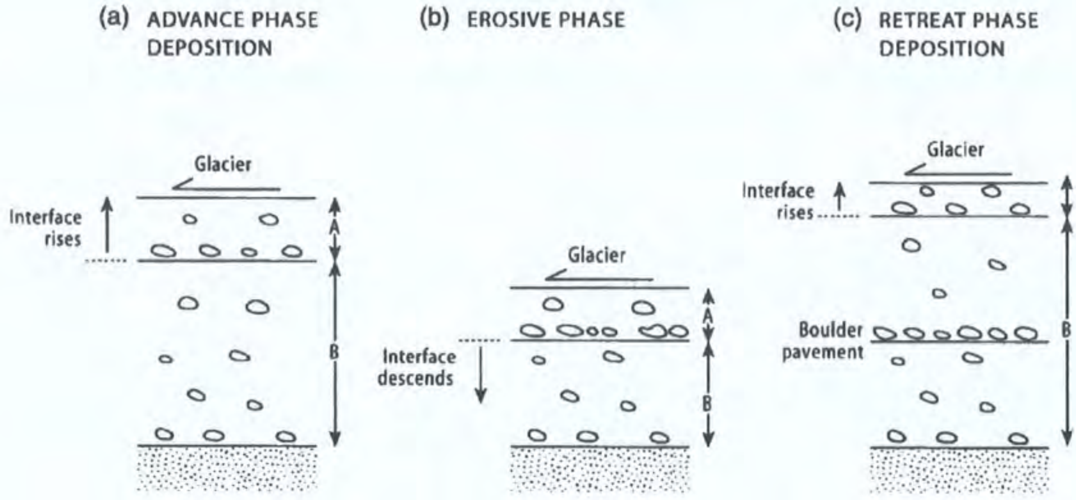


Figure 5.8. Theoretical model illustrating the production of a clast pavement within subglacial till. (a) The A/B interface rises during advance phase till deposition. (b) The A/B interface descends during an erosive phase and clasts become concentrated. (c) The A/B interface rises again as till is deposited during the retreat phase, isolating the clasts. Boulton, 1996a, p.60.

A number of mechanisms have been suggested to explain the occurrence of clast lags and boulder pavements, such as the one found between Facies 1 and 3 at Site 3. Boulton (1996a) proposes that boulder pavements within a subglacially deformed till mark the lowest level to which the A/B interface descends during an erosional phase (Figure 5.8), where boulders become concentrated as the A/B plane descends and then become isolated within the till as the A/B interface rises during subsequent till deposition. Clark (1991) however, suggests that large clasts will sink through an unconsolidated deforming till layer until they reach a point at which the till matrix is able to support their weight. Alternatively, other workers have suggested the production of clast lags can be caused by a process of winnowing, where meltwater flushing, potentially within subglacial canals, can remove the till matrix (Evans *et al.*, 2006). Differences in the structural and geochemical composition of tills above and below the clast lag at Site 3 support the notion that the clast lag represents an erosional interface between an advance and retreat phase till. Alternatively, the formation of the clast lag through the winnowing of finer sediments due to subglacial meltwater drainage is consistent with the existence of subglacial canal and channel fills at this location.

Piotrowski and Kraus (1997) propose a model of glacier bed conditions in which processes of subglacial sliding co-exist with patches or 'sticky' spots of deforming sediments. Spatial variability in frictional conditions at the glacier base can reflect till inhomogenity, changes in bed roughness, and subglacial drainage patterns (Evans *et al.*, 2006). For example, the variability of drainage conditions at the glacier bed leads to changes in pore water pressure within the subglacial sediments. Although decoupling of the ice from its bed will ultimately occur following an increase in pore water pressure, as pore water pressures rise, a decrease in the cohesive strength of the sediments causes deformation to occur (Evans *et al.*, 2006). The discontinuous sand lens within Facies 1 at the southern section of Site 1 may reflect ice-bed decoupling and sliding, juxtaposed with areas of ice-bed coupling and till deformation. This model of variable bed conditions may therefore be applicable in describing conditions beneath the North Sea ice lobe at Skipsea.

Overview

Geochemical analysis of the diamictons at Skipsea indicates that in general basal diamictons can be distinguished from the upper diamictons by subtle differences in the abundances of elements within the matrix. This supports the model of subglacial deformation of an accreting till layer (Evans *et al.*, 1995), and changes in till composition upwards in a sediment sequence (Boulton, 1996a,b). Initial glacial excavation of pre-existing sediments (i.e. Basement Till and Dimlington Silts) is invoked to explain the lack of chalk clasts within the lower diamicton at Sites 1 and 3, where the pre-existing sediments were incorporated into the active layer (i.e. Skipsea Till) (Hart & Boulton, 1991; Eyles *et al.* 1994; Evans *et al.* 2006).

Excavation of the pre-existing material is likely to have continued until the chalk bedrock was reached and subsequent quarrying of this substrate would have occurred. Hart and Boulton (1991) envisage that subsequent deposition of both local and far travelled material will cause the pre-existing material to become sheared out, until the sediments deposited eventually consist of predominantly far travelled material. At this stage, the diamicton is homogenous due to intense deformation. This explains the increased chalk and limestone clasts further up in the sequence, where chalk is of very local origin and limestone is from further north. This is also reflected in the geochemical signal by the differences between Facies 1 and 2.

However, the geochemical signature also demonstrates that there is not a smooth progressive change in till composition as predicted by Boulton (1996a,b). The different geochemical signature of samples from the lower till at Site 1 (Facies 1) compared to any other till units, suggests that rafts of lithologically distinct material occur within the sediment pile. These rafts may have been deposited due to the re-working of pre-existing lithologically distinct sediment remaining from a previous ice advance, or following a slight change in ice flow direction, where new material is brought in from a different source area. However, similarities between the upper and lower tills (Facies 1 and 3) at Site 3 and the upper tills (Facies 2) at Site 1 demonstrate that varying degrees of mixing of these distinct rafts has taken place.

The sediment section above the diamicton (Facies 2) at Site 2 denotes the infilling of a sag basin at Skipsea which is comparable to sediment sequences found at Barmston and inland at Gembling and Gransmoor (Walker *et al.*, 1993; Evans *et al.*, 1995; Thomson & Evans, 2001). The initial infilling of this depression by a decimetre thick veneer of horizontally to low-angle bedded sands, represents the deposition of a subaqueous outwash fan, which is likely to have occurred within an ice-marginal lake during deglaciation (Thomson & Evans, 2001). The subsequent deposition of sand and clay rhythmites reflect seasonal fluctuations in discharge (Rushworth, 1998) during the infilling of depressions in the till surface. Intense faulting and folding occurred after these sediments had been deposited, potentially indicating melt-out of buried ice. The low-angle cross-bedded sands and gravels towards the top of the sequence reflect deposition of sediments by slow moving water on an extensive sandur following the infilling of the basin (Evans *et al.*, 1995; Thomson & Evans, 2001).

5.4 Filey Brigg

Edwards (1981) proposes that the Lower Series and Upper Series tills within Filey Bay correlate with the Skipsea and Withernsea tills of Holderness, and are separated by a unit of sands and gravels. Alternatively, Evans *et al.* (1995) suggest that the succession at Filey Brigg is composed mainly of one diamicton, which is interspersed with beds of a laminated diamicton and tentatively correlated with the Skipsea Till. The present research found that at Site 1, diamicton within Facies 6, above the sand and gravel unit, was lighter and redder than diamicton within Facies 4, changing from dark brown (10YR 4/3) to red brown (7.5YR 3/3). Particle size analysis at the site also revealed distinct differences between Facies 4 and Facies 6, where the lower diamicton was found to be sandier than the upper diamicton. Both the changes in colour and particle size results therefore support Edwards' (1981) proposal that both the Skipsea and

Withersea tills are present at Filey. Cluster analysis performed on the geochemistry results demonstrates that, in general, most samples from Facies 4 are similar to each other, and the majority of samples from Facies 6 also tend to cluster together. However, an additional laminated diamicton unit (Facies 5) was also found below the sand and gravel unit, where laminations are caused by continuous sand stringers with no internal structure, which concurs with research by Evans *et al.* (1995). Geochemical analysis reveals that compared to the suites of elements found within the laminated diamicton samples, the geochemical composition of Facies 4 and Facies 6 is much more similar. In addition, Facies 4 and 6 were also found to generally possess different geochemical signatures from the diamictons at Site 3 (Facies 1-3) and Site 2 (Facies 7), indicating that the petrography and genesis of the diamictons within the succession at Filey is probably more complicated than the traditional two-tiered layer cake stratigraphy.

Evans *et al.* (1995) suggest, based on micromorphological analysis, that the sediments at Filey Brigg have been subjected to intense shearing, and differences upwards in the sequence are a result of differential deformation. They also discovered that the laminated diamicton unit possessed a variable anisotropy, which they associated with differential consolidation, either due to areas of dewatering, where fine silts accumulated in pore spaces between sand grains, or to variations in strain during deformation. It is possible that this may explain why the particle size distributions of samples from Facies 5 are remarkably dissimilar.

The existence of sand stringers at Site 3 indicates that the sediments have been subject to intense shear during deposition (Boulton *et al.*, 2001). These laminations highlight large open, overturned, chevron and sheath folds, which indicate that glacitectonic compression has occurred, causing ductile deformation (Benn & Evans, 1998; McCarroll & Rijsdijk, 2003). Distinct changes in colour distinguish three diamicton units (Facies 1-3). Although moisture content is likely to be a component of this colour variation, the differences are enough to signify that they may also reflect the incorporation of lithologically distinct layers. Results from particle size analysis also show that these three facies contain different particle size ranges. However, the diamictons cannot be differentiated using geochemistry, implying that mixing has occurred between the boundaries, as at Dimlington (*cf.* Hooyer & Iverson, 2000). At Site 1, the incorporation of lithologically distinct rafts of material into the sediment pile may also explain differences in the geochemistry of some of the samples, where frequent folding episodes and attenuation due to high strain rates may have removed any visible boundaries or rafts, homogenising particle size distributions and giving the till a massive appearance (Boulton, 1987; van der Meer, 1993; Hiemstra & Rijsdijk, 2003).

At Site 3, the rapid transition from heavily laminated and folded diamicton into massive diamicton could indicate an increase in cumulative strain upwards (Ó Cofaigh & Evans, 2001), where pre-existing sand sediments have been homogenised (Hart & Boulton, 1991; Benn & Evans, 1996). Alternatively, the massive appearance could be due to a lack of intense weathering from wave action in the higher parts of the cliff, causing sand laminations to remain concealed (Evans *et al.*, 2006). This could also be the case at Site 1, where the occurrence of occasional sand laminations could indicate the presence of a series of much thinner, macroscopically invisible, sand partings.

The teardrop-shaped nature of the gravels found within the diamicton in Facies 3, resting above and around the chevron fold, possesses some characteristics associated with a density-driven deformation style (Rijsdijk, 2001; McCarroll & Rijsdijk, 2003). However, the intense folding of the underlying diamicton suggests that its deposition within a subaqueous environment, as at Dimlington Site 2, is unlikely (Boulton *et al.*, 2001). It is conceivable, however, that initial deformation of the underlying diamicton occurred through compressive deformation, followed by subsequent accentuation of this folding as the gravel sank towards the centre of the syncline, thereby increasing loading in this area (Rijsdijk, 2001) and creating the tight chevron fold. This would require the underlying till to behave in a semi-viscous, and ductile manner.

Overview

The origin of the sand and gravel unit midway up the cliffs at Filey Brigg is unclear. Previous workers have assigned it to fluvial (Harrison, 1895), marine (Wood, 1871) and englacial (Carruthers, 1939) environments. More recently, Edwards (1991) suggested that they were deposited by meltwater flowing through an englacial conduit between the ice sheets that deposited the Skipsea and Withernsea tills, whilst Evans *et al.* (1995) interpreted the stratified sediments as subglacial channel or cavity fills. The discontinuous nature of the sediments within the unit lends itself towards deposition within a subglacial channel followed by deformation. Evans *et al.* (1995) also found units of stratified sediments repeated upwards in the sequence, supporting this notion. Alternatively, the extensive nature of the unit as a whole could imply that the sediments actually record an ice-free period. The upward fining of the sequence from gravels to laminated sands could indicate a transition from a proximal to distal position away from the ice sheet (Bouma, 1962; Walker, 1992). Fluctuations between granules, sands and clays towards the top of the sequence imply changes in flow velocity, perhaps during glacier readvance (Benn & Evans, 1998). The deposition of a second till unit of relatively similar provenance could explain the slight differences in the geochemical signatures of the upper and lower diamicton. Incorporation of the pre-existing lower till unit into the subglacial traction layer of the ice that deposited the second till unit, combined with an increasing influx of more distal material similar in geochemical signal to the far-travelled component of the lower unit, could have occurred. Overriding, erosion and cannibalisation of the upper layers of the stratified sediments could have occurred in a similar fashion to processes at Dimlington, depositing rafts of the sediments higher up in the sequence.

5.5 South Ferriby

Samples taken from the lower diamicton (Facies 1) at the two sites in South Ferriby display great similarity in terms of colour, particle size and matrix geochemistry. Two interpretations for the environment in which they were deposited are proposed. Firstly, it is likely that the initial flux of sediment from the North Sea ice sheet was deposited in a proglacial lake, due to damming of the Humber Gap. This implies that the lower diamicton was deposited subaqueously. The massive nature of the diamicton suggests that it may represent the former plug zone of a cohesive debris flow (Benn & Evans, 1998) within the distal zone of a glaciomarine environment (Hart & Roberts, 1994). The concentration of clasts within the basal layers of the diamicton can be explained by the sinking of large clasts through the weak sediment (C.H. Eyles, 1987; N. Eyles, 1987; Ghibaudo, 1992). Alternatively, the massive structure of the lower diamicton indicates a subglacial origin (Ó Cofaigh & Evans, 2001; Boulton, 1996a), where the concentration of large chalk clasts in the basal layers may have been caused by glacial excavation and shearing of the bedrock. This implies that any pre-existing sediments at the site were incorporated into the diamicton and intensively mixed (Boulton, 1996a).

Evidence of ripples within the sand laminations of the second diamicton unit (Facies 2) agrees with previous authors' suggestions that this unit was deposited within flowing water (Stather, 1896; Frederick *et al.*, 2001). However, it is still unclear whether these sediments are derived from a proglacial or englacial environment. Differences in the geochemical signatures between the laminated units at Sites 1 and 2 could be due to the variable nature of the sediments, where the samples analysed could have contained different proportions of sand and diamicton. The slight differences in the geochemical composition of Facies 1 and 3 could provide evidence for a period of ice retreat in between the deposition of the two units. The difference is slight, however, and is not enough to conclude that the upper and lower diamictons are lithologically distinct, agreeing with work by Madgett (1975). Therefore, although evidence for ice retreat is inconclusive, any potential ice readvance is likely to have originated from a similar source area.

5.6 Kirmington

The section at Kirmington reveals a 1.3m thick sequence of massive diamicton, which rests upon interglacial beach deposits (Catt, 2007). Results from geochemical analysis at Kirmington demonstrate that the diamicton unit contains similar proportions of elements throughout. Despite particle size analysis revealing differences in the particle size distribution of the lower (Facies 1) and upper units (Facies 2), geochemistry shows that weathering has caused little change in element abundances in the upper layers. This suggests that weathering at Kirmington has been less extensive than at South Ferriby or Morston. Overall, the diamicton matrix at Kirmington is found to be geochemically very similar to some of the samples at Welton-Le-Wold, and the lower diamicton at South Ferriby. Despite the inference that the diamictons are similar due to their high chalk content, Figures 4.44, 4.45, 4.50 and 4.51 show that diamictons from these three sites contain similar abundances of most elements.

5.7 Welton-Le-Wold

A dark brown fine-sediment diamicton (Facies 1) forms the basal layers of the Welton-Le-Wold section, where incomplete mixing displays rafts of clay interdigitated with dark brown diamicton. This unit is interpreted as glacitectonite, due to the retainment of pre-existing structural characteristics (Evans *et al.*, 2006). The existence of this sediment at the base of the Late Devensian till sequence at Welton-Le-Wold, suggests that ponding occurred within the proglacial environment before the ice sheet overrode the landscape, as at Dimlington and South Ferriby.

The nature of clustering in the geochemical analysis indicates that there are subtle changes in the proportions of elements in parts of the section at Welton-Le-Wold. The grouping of sample W1.1, from the glacitectonite at the base of the section, with samples higher up in Facies 2, suggests that as the ice sheet moved over the pre-existing sediments it began to incorporate these into the subglacial traction layer, and rafts of pre-existing material were elevated to higher positions in the sediment pile. Intense shearing and mixing have left the changes in till petrography macroscopically invisible. Comparison with other locations shows that the suite of elements within the glacitectonite and associated samples is most similar to samples from the laminated and upper diamicton units (Facies 2 and 3) at South Ferriby. Other samples at Welton-Le-Wold are found to be most similar to diamictons from Kirmington and the basal section (Facies 1) at South Ferriby. It is perceived that this could be due increases in chalk content within the samples, but Figures 4.45 and 4.51 show that although this group (CW2 or WW2) contains slightly higher proportions of calcium than the group containing the glacitectonite (CW1 or WW1), abundances of other elements are more influential in clustering these groups of samples together.

5.8 Morston

The diamicton at Morston is divided into two sub-units based upon colour and clast content. Work by Gale *et al.* (1986, 1988) suggested that the upper part of the Hunstanton Till (Facies 2) in the exposure at Morston had been reworked. Particle size analysis of Facies 1 and 2 demonstrates large differences in their particle size distributions (see Figure 4.84). Results from geochemical analysis, however, show that the two units contain very similar element abundances, supporting the proposal that Facies 2 has been reworked from the underlying diamicton (Gale *et al.*, 1988).

The whole diamicton section (Facies 1 and 2) at Morston was originally correlated with the Hessle Till in Yorkshire (Soloman, 1931, 1932), and Gale *et al.* (1988) suggested that the absence of chalk and marine fossils indicated that the diamicton had been subject to intense weathering. Geochemical analysis clustered the diamictons (Facies 1 and 2) at Morston with a sample taken from weathered diamicton (Facies 4) at South Ferriby, thereby demonstrating the weathered nature of the whole diamicton sequence at Morston. This also suggests that the diamicton at Morston is of similar geochemical composition to other tills in Lincolnshire.

Chapter 6: Discussion

6.1 Examination of the complexity of the eastern England till sequences

At Dimlington, and other sites along the coast, the Skipsea Till contains a number of different units, which display a wide range of characteristics in terms of colour, structure, and clast lithology. This variation was previously noted, in particular, by Bisat (Madgett & Catt, 1981) (Figure 5.1), and Berridge and Pattison (1994). Madgett and Catt (1978) also recognised the variable nature of the Skipsea Till. Geochemical analysis supports the argument that there are prominent variations in the composition of the Skipsea Till. It is suggested in Sections 5.1 and 5.2 that this complexity is caused by initial excavation and deposition of pre-existing Quaternary sediments (i.e. glacial till, glacial outwash, organic sediments) and local material (chalk bedrock), followed by the deposition of sediment from more distal sources (i.e. limestone, shale and mudstone lithologies) (Hart & Boulton, 1991; Boulton 1996a,b).

The geochemistry also reveals that the variation between units of the Skipsea Till is often much greater than the variation in geochemical composition between the Skipsea and Withernsea tills. Boulton (1996a,b) suggests that till initially deposited in a particular location will consist of local lithologies, and will progressively change composition upwards as more far travelled sediment arrives at the site. Therefore, excavation and incorporation of the Skipsea Till into the basal layers of the Withernsea Till, following the readvance of the North Sea ice sheet, is likely to be one reason for their similarity. In addition, the repeated geochemical signatures within the Withernsea Till suggest that the tills have been intensely folded, and rafts of sediment may have been elevated into higher positions by tectonic transposition (van der Wateren, 1995, 2003; Evans & Ó Cofaigh, 2003; McCarroll & Rijsdijk, 2003).

More broadly, results of the geochemical analysis show that the tills can be divided into two key groups. Samples taken from chalk-rich Skipsea Till at Dimlington and Skipsea are found to contain very similar abundances of elements to samples taken from South Ferriby, Kirmington and Welton-Le-Wold, which are assigned to the Marsh Till (Straw, 1969). Secondly, the geochemical composition of the dark, grey-brown diamictons from the Skipsea Till are found to bear great resemblance to the upper and lower diamictons at Filey Site 1, and some correspondence to some samples from Welton-Le-Wold, and samples from the laminated and upper diamictons at South Ferriby.

Initially, it appears that this grouping is based on the amount of chalk found within the till units. This concurs with work by Burek and Cubitt (1991), who demonstrate that British tills can be differentiated between calcium-rich tills on the east coast of England, and tills with low CaO percentages west of the Pennines. Further investigation of abundances of elements within these two groups shows however, that this is a generalisation. The group of 'chalk-poor' diamictons does contain slightly lower abundances of Ca and Sr, but also exhibits a lower abundance of Rb, and higher abundances of Fe, Al, Ti, Li, Be, B, V, Cr, Mn, Co, Ni, Cu, As, Zr, Nb, Mo, Sn, Ga, Pb, Bi, U, Ba (see Figures 4.44, 4.45, 4.50 and 4.51).

Burek and Cubitt (1991, p.471) propose that "all glacial deposits are immature", where glacial sediments are originally derived from rock fragments through mechanical break-up and weathering. They suggest that only the finer fractions will contain a rich assemblage of elements. The greater abundance of chalk clasts in some till units compared to others in eastern England may signify that they are more directly derived from chalk bedrock excavation (local sources), and have undergone less re-working and mixing with more distal material. For example, sample D4.10, from Dimlington, is a very white diamicton that contains very few clasts other than chalk (Figure 4.9). It is shown to possess very high abundances of Ca, and generally very low abundances of most other elements, demonstrating that limited mixing has occurred. Therefore, the higher abundances of elements in the 'chalk-poor' group of tills indicate that the sediments are more geochemically mature than the 'chalk-rich' tills and suggest that these tills contain a more far travelled geochemical signature.

Differences between the 'chalk-rich' and 'chalk-poor' tills could also be explained by changes in provenance of the ice depositing these till units, whereby ice originating to the east in the North Sea basin would have moved over a much larger expanse of chalk bedrock before reaching the present east England coast, than is the case with ice moving directly southwards (see Figures 1.5 and 1.6). Evidence for an oscillating ice margin at Dimlington (*c.f.* Section 5.1) suggests that changes in glacier provenance could be explained by a change in the dominance of ice lobes within the North Sea basin. Mixing of pre-existing Quaternary sediments with new, lithologically distinct far travelled material, following an ice lobe advance may explain the complexity of the geochemical signature found along the east coast. Figure 6.1 provides a theoretical model of changes in the location and extent of these ice lobes over time. Geochemical data from this research is currently unable to reconstruct specific ice flow paths and therefore the model acts to demonstrate how changes in the dominance of ice lobes from varying source areas may bring in new lithologically distinct sediments, whilst incorporating material deposited by a previous flow lobe, causing the geochemical signature to become a synthesis of pre-existing, local and far travelled material from varying source locations.

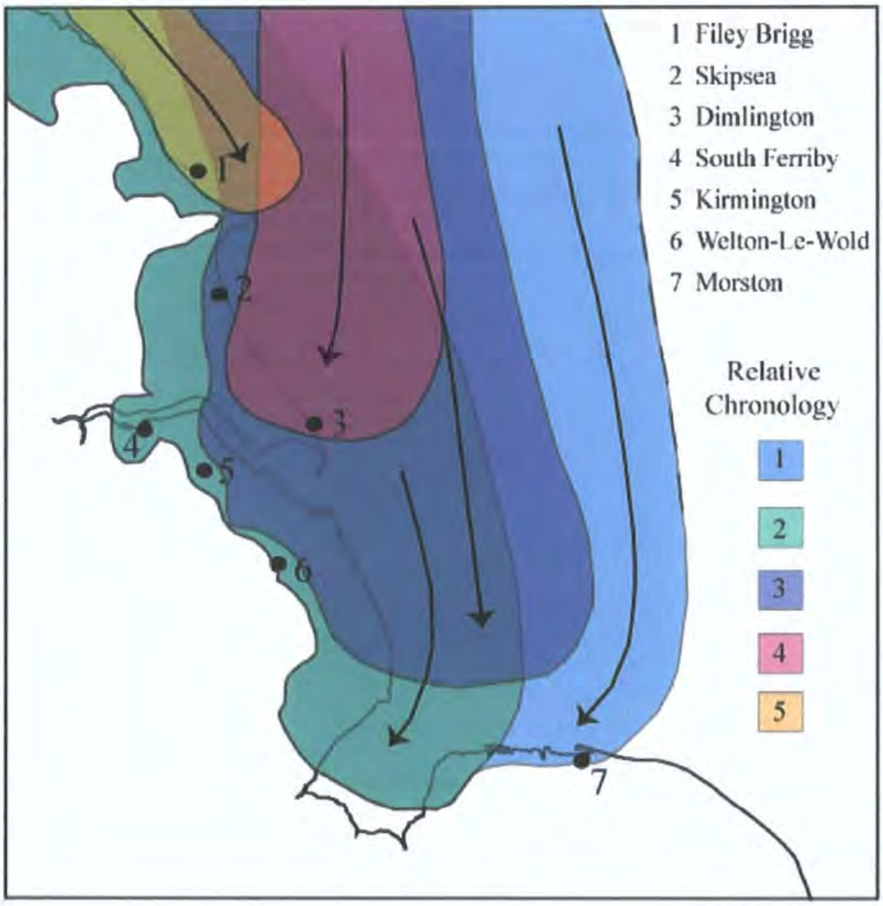


Figure 6.1. Idealised model of ice flow unit positions over time, illustrating how these units both incorporate pre-existing sediment deposited by a previous flow unit, and bring in new material from different source locations.

Changes in the dominance of ice flow lobes over a particular area are often associated with surging glaciers i.e. in Svalbard where looped medial moraines record these changes (Croot, 1988). Whilst results of this research are unable to confirm that the Late Devensian ice margin in this region surged (*cf.* Eyles *et al.*, 1994), the suggestion of changing ice-flow lobe patterns does support, at least in part, a surging hypothesis.

Other evidence for surging in the region is provided by various authors including Boulton *et al.* (1977), Straw (1979) and Eyles *et al.* (1994) and is summarised below.

Clay-rich, soft sediment beds have been cited as a source of ice sheet instability, due to the effectiveness of clay lithologies to restrict drainage and maintain low effective pressures and deformation (Boulton, 1996a), and modeling of the Late Devensian British Ice Sheet by Boulton *et al.* (1977) recognized that the southerly movement of the North Sea ice lobe could not be reproduced under steady-state conditions. Boulton (1996b) also proposed that soft sediments will cause a draw down of the ice surface, which will increase ablation rates and impede ice sheet advance. In order for advance to continue, Boulton (1996b) suggested that a low ELA and high ablation gradient are required, whilst Straw (1979) employed surging as a mechanism to explain the extensive southerly limit of an ice sheet with such a low profile.

Rapid advance of an ice margin into areas of soft sediment has been proposed to result in the thrusting and stacking of glacitectonites (Evans & Ó Cofaigh, 2003). Sedimentological and geochemical analyses of the diamictons at Dimlington reveal a repeated vertical sequence of similar layers of sediment indicating the folding and thrusting of pre-existing material into elevated positions in the sediment pile, and points to the formation of a push moraine at Dimlington High Land (*c.f.* van der Wateren, 1995). The production of glacitectonically constructed moraines is often associated with surging glacier margins (e.g. Lamplugh, 1911; Boulton *et al.*, 1996; Evans & Ó Cofaigh, 2003; Evans & Rea, 2003), but these features have also been found at stable margins e.g. in polar and sub-polar regions due to high stresses within frozen proglacial sediments (Evans & England, 1991; Ó Cofaigh *et al.*, 2003). Van der Wateren (1995) concludes that the ice advance required to produce a push moraine can be the result of either continental scale glaciological conditions, such as a positive mass balance, or local conditions such as a surge. Therefore, although possible, the production of push moraines alone is not diagnostic of surging activity (Evans & Ó Cofaigh, 2003; Evans & Rea, 2003).

Glacilacustrine sediments found at Dimlington provide evidence for a period of ice-free conditions, before a second advance of the North Sea ice lobe into the area. Ice-dammed and proglacial lakes often occur around the margins of surging glaciers, filling topographic depressions produced during the previous surge (Evans & Ó Cofaigh, 2003). In addition, proglacial lakes have been cited as an important trigger for surging, causing ice-margin flotation and destabilisation (Dredge & Cowan, 1989). Other evidence for glacier surging in the region has been cited by Eyles *et al.* (1994) to include hummocky topography and till diapirs formed by the *in situ* downwasting of stagnant ice, and upward extrusion of sediments between shallow basins on the surface of the Skipsea Till. However, this geomorphological evidence for surging is indirect and although the saturated substrate over which the North Sea lobe advanced would have facilitated surging, the evidence is not conclusive.

6.2 Application to Boulton's (1996a,b) theory of changes in till composition

Boulton (1996a,b) predicts that within a zone of deposition, the source of the lithological components of the till sequence will progress from local to far-travelled material, providing no folding occurs. In his Zone 3, lithologically distinct advance and retreat phase tills will be separated by an erosional interface, where the advance phase till consists predominantly of local lithologies (see Figure 1.3). At the ice-margin, in Zone 4, these lithological units will appear to grade into each other, reflecting continuous deposition. Boulton (1996a,b) also proposes that the thickest till sequences will occur in the submarginal zone of an ice sheet due to an increase in the rate of deposition towards the margin.

The sediment sequences found in east Yorkshire and Lincolnshire, in general, support these predictions. The thickest till sequences occur along the east Yorkshire coast (Zone 3), and till thickness generally decreases southwards towards the ice limit in Lincolnshire and Norfolk (Zone 4). The similarity of the geochemical composition of diamictons at South Ferriby, Kirmington and Welton-Le-Wold and their clustering with chalk-rich diamictons at Skipsea and Dimlington supports the notion that the tills are composed of material predominantly local in origin, inferring that they are deposited as advance phase tills and that ice retreat occurred before sediment packages from more distal sources reached these locations. The diamicton at Morston also shows a similar geochemical composition to these sites, although comparison is hindered by its weathered nature.

Changes in till composition within the sequence at Skipsea demonstrate distinct lithological differences between the upper and lower units at Sites 1 and 3, which could reflect a sequence of advance and retreat phase tills at this location. In particular, at Site 3, a clast lag separates two geochemically distinct till units, which may indicate a period of erosion between the deposition of advance and retreat phase tills. Boulton's (1996a,b) model is supported by evidence to suggest that changes in till composition are associated with the initial re-working of pre-existing material, followed by the excavation of local bedrock, and the incorporation of material of more distal provenance (Hart & Boulton, 1991) (*cf.* Section 5.2). The similarity of element abundances within the lower till (Facies 1) at Site 3 and samples from the upper till (Facies 2) at Site 1, as well as the individuality of the lower till (also Facies 1) at Site 1, indicate that varying degrees of mixing and incorporation of rafts of lithologically distinct material has occurred, which causes the succession to diverge away from the theoretical model slightly.

Similarly, at Dimlington, although the tectonic thrusting and stacking of the subglacial tills complicate the sequence, the lower till units (=Skipsea Till) exhibit a transition from local (predominantly chalk-derived geochemical signal) to more far travelled material (more diverse geochemical signature). For example, it is suggested that differences in the geochemical composition of the chalk-rich till unit (Facies 1) and darker till unit (Facies 2) at Sites 2 and 3 could be due to relative differences in the maturity of the till matrix, and is related to a longer transport time of the upper unit. However, the existence of fold structures within Facies 2 demonstrates that the till has not been transported for long enough to thoroughly mix and homogenise the sediments (Boulton, 1996a), indicating that deposition occurred shortly after the incorporation of local and pre-existing Quaternary material with more far travelled sediments. The presence of glacilacustrine sediments above Facies 2, the differences in geochemical signature between it and Facies 1 below, and the distinct contact between Facies 1 and 2 suggests that the upper dark till (Facies 2) could represent a retreat phase till.

A transition in the geochemical composition of the traditional Withernsea Till is not observed; instead geochemical analysis reveals repeated geochemical signatures upwards in the sediment pile which often correspond with the geochemical signature of till lower in the sequence, including that from the traditional Basement and Skipsea Tills. This suggests that the ice lobe that deposited the traditional Withernsea Till incorporated rafts of pre-existing material (i.e. Skipsea Till and subsequently Basement Till) during excavation, which were elevated to higher positions within the sediment sequence through stacking and folding. Subtle changes in the geochemical signature within the Withernsea Till compared to the Skipsea and Basement Tills suggests that distal material, possibly from a new source area, was also incorporated with the pre-existing Quaternary sediments and mixed to varying degrees.

At Filey Brigg, subtle geochemical differences between the upper and lower tills (Facies 6 and Facies 4) at Site 1 indicate that the sands and gravels between them may represent retreat of the glacier margin. However, the general similarity of these two till units compared to the samples from the laminated diamicton (Facies 5) and sporadic samples from within Facies 4 and 6, suggest that the geochemical differences are slight. The whole sequence at Filey therefore suggests that there may be changes in till lithology upwards in the sediment sequence. However, the rafting and incomplete mixing of lithologically distinct material, in addition to the sand and gravel hiatus, causes the sequence to be interrupted and complicated. Therefore no clear signal for progressive changes in till lithology is observed at Filey.

Overall, these results broadly support Boulton's model in that they suggest generally that the geochemistry of the till matrix will progressively change upwards in a sequence from a local to distal provenance, due to the progressive mixing of more far travelled sediments with local material. However, in reality, incomplete mixing of pre-existing sediments with new sediment packages, followed by the stacking, folding and attenuation of these units, complicates the sequence, and therefore a progressive change in geochemical signature is often difficult to decipher or not observed at all.

6.3 Implications for eastern England Devensian stratigraphy

In the field, the distinct differences between the matrix colours of the Basement, Skipsea and Withernsea tills were observed. Particle size analysis in this research, however, demonstrates that although there are some differences between the particle size distributions of the traditional till types and other sub-units, in general, they are not distinct enough to differentiate between till units as suggested in previous work (e.g. Catt & Penny, 1966; Madgett & Catt, 1978) (see Figure 2.2).

Geochemical analysis also reveals that the till matrix geochemistry does not generally allow differentiation between the traditional till units. Internal geochemical variations within the traditional Skipsea Till are often greater than any differences between it and the Withernsea Till. Conversely geochemical similarities are found between the Withernsea Till and samples from till units much lower in the sediment pile. This repetition of geochemical signatures upwards and the lateral discontinuity of some lithologically distinct units, therefore suggests, that the till sequences, particularly at Filey, Dimlington and Skipsea, are comprised of lithologically distinct layers of material which have been mixed, folded, or stacked into higher positions within the sediment pile. The geochemical groupings of tills in eastern England are therefore found not to correspond identically to the traditional division of Late Devensian tills by Madgett and Catt (1978) in Holderness (Skipsea Till and Withernsea Till), by Straw (1969) in Lincolnshire (Upper and Lower Marsh Tills), and by Edwards (1981) in Filey Bay (Upper and Lower Series Tills).

Previous research has differentiated the Skipsea and Withernsea tills based upon their petrography, particle size distributions, clast lithologies and colour (e.g. Catt & Penny, 1966; Madgett & Catt, 1978). It is important to note that in most of this research these techniques have been employed to differentiate between pre-defined stratigraphic units, rather than used to differentiate the sequence into geochemical units, as in this research. Particle size results in the current research illustrates this point as discussed above, where it was found that the traditional till units could be differentiated to a degree, but that the differences between units were not great enough to be able to differentiate between them using particle size analysis alone. Results were similar for the geochemical analysis, although differentiation between the traditional units was even less. It is therefore argued that this research provides a more objective approach to till differentiation than previous work.

The origin of the tills in eastern England, predominantly based upon the results of clast lithology and heavy mineral analysis, is correlated to geomorphological evidence of flow pathways southwards from Scotland and from the west through the Stainmore Gap (e.g. Clark *et al.* 2004). Recent research suggests ice arriving on the east coast of England was sourced from north-western England, the western Southern Uplands, the eastern Grampians and possibly north-eastern Scotland (Davies *et al.*, *in press*). The scope of the geochemical analysis in this research at present is only able to investigate geochemical signatures at a local level and therefore the origins of far travelled material must be inferred from other available research such as Catt and Penny (1966), Madgett and Catt (1978), Davies *et al.* (*in press*). This research enhances this and other work on the east coast of England by providing a detailed local analysis of till composition and ice dynamics. It suggests that any ice flowing southwards along the coast of eastern England will incorporate pre-existing Quaternary material, excavate local bedrock and bring in new sediment from its respective source area. However, it argues that following several ice lobe advances or changing patterns of ice lobe dominance, the geochemical signal in the sediment deposited by each ice lobe will be such a blend of pre-existing, local and far travelled material, that extracting the exact source of a particular ice lobe is virtually impossible. Previous provenancing work based upon clast lithological and heavy mineral analysis, may therefore over-simplify the complexity of the geochemical signature.

The present research therefore proposes that the till sequences along the east coast of England relate to the deposition of till beneath an oscillating ice margin, and in this respect, the traditional division of the Skipsea and Withernsea Tills and their equivalents north and south may still be valid. However, geochemical and particle size analysis results suggest that the incorporation of pre-existing sediments into the subglacial traction layer, and the progressive mixing of more distal sediment packages has caused a much more complicated geochemical signature than a simple two till division, where geochemically distinct till layers are suggested to be the product of changes in ice lobe dominance and oscillations. The traditional Skipsea and Withernsea (and to an extent the Basement) till types should therefore, no longer be considered as lithologically distinct units.

Chapter 7: Conclusion

In general, the diamictons in eastern England studied in this investigation are interpreted as a sequence of subglacially deformed tills, which contain a number of lithologically distinct till units. Intervening stratified sediments are interpreted variously. At Dimlington, the transition from massive diamicton into laminated clay and sand provides evidence for an ice-free period and the deposition of these sediments within a proglacial lake environment. The interdigitating nature of till and stratified sediment units at the southern end of the latter suggests that the ice margin oscillated on at least one occasion into the lake before subsequent readvance and overriding of the lake sediments. Intra-till stratified sediments at Skipsea are likened to cavity-fill features (Alley, 1991; Clark & Walder, 1994) and agree with the proposal by Evans *et al.* (1995) that they represent deposition by a migrating subglacial drainage network. At Filey, the origin of the intervening sand and gravel unit is ambiguous. The stratified sediments may either represent subglacial drainage channels as at Skipsea and suggested by Evans *et al.* (1995), or they may also represent an ice-free period as at Dimlington.

Geochemical analysis demonstrates that the geochemistry of the till matrix across Lincolnshire is, in general, relatively uniform and is likely to be related to the unvarying nature of the chalk bedrock throughout most of this region. The geochemical signatures of tills at South Ferriby, Welton-Le-Wold, Kirmington and Morston display a high level of similarity. At these four sites two key groups of geochemically similar diamictons are established. The first contains samples that appear to be richer in chalk within the Kirmington section, the basal diamicton (Facies 1) at South Ferriby and some samples from Facies 2 at Welton-Le-Wold. Further investigation shows that as well as containing higher abundances of chalk, these samples are much lower in a number of element abundances than the second geochemical group, which contains samples from the laminated (Facies 2) and upper (Facies 3) diamictons at South Ferriby and the remaining samples from Welton-Le-Wold. This second group of samples is also shown to possess a strong affinity with tills from Filey Brigg. In addition, samples from Morston are found to display a great similarity with samples from the weathered diamicton (Facies 4) at South Ferriby, demonstrating the weathered nature of the thin till section at this site.

The greatest variation in till matrix geochemistry occurs at Dimlington, where the diamictons can be divided into five main geochemical groups. Again, these groups initially appear to be influenced by chalk levels within the tills, but further investigation demonstrates that variations in a large number of other elements have also caused this grouping. The traditional Skipsea till type is found to contain a number of sub-units similar to those found by Bisat in the 1930s, confirming the complexity of this till unit. The Withernsea Till unit is macroscopically more uniform, but geochemical analysis indicates a chaotic geochemical signature, particularly within the middle part of this unit. In addition, the geochemical groups also suggest that weathered tills at the top of the Dimlington cliffs contain similar element abundances to tills at the base of the section. Although changes in geochemical composition by weathering may have coincidently caused this similarity, similar abundances of a large number of elements within these two till units suggest the possibility that basal tills may have been elevated to higher levels within the sequence due to glacitectonic folding.

The repeated and chaotic geochemical signature both laterally and vertically within a number of till sequences implies that rafts of lithologically distinct pre-existing Quaternary material have been cannibalised and progressively mixed with local bedrock and more distal sediment packages to create a sequence of tectonically folded and stacked tills (Hart & Boulton, 1991; van der Wateren, 1995; Boulton, 1996a, b), and supports the hypothesis that the Late Devensian tills in eastern England are much more complex than the traditional view (Evans *et al.*, 1995). This mechanism of till deposition suggests that the increase in Withernsea Till thickness at Dimlington High Land marks the position of a glacitectonically folded push moraine (Aber *et al.*, 1989; van der Wateren, 1995, 2003).

Evidence for a transition from local (predominantly chalk-derived) to far travelled material (shales, mudstones etc.) predicted by Boulton's (1996a,b) model is found at Dimlington, Skipsea and Filey. Varying degrees of tectonic folding and incomplete mixing of lithologically distinct rafts of material at these sites have, however, complicated the geochemical signal. At Skipsea geochemical differences within the till sequence suggest that the basal till may represent an advance phase till and that the upper till was deposited during the retreat phase. This is particularly the case at Site 3 where a clast lag separates two geochemically distinct till units. At Filey, geochemical differences between the lower and upper tills are less distinct and rafts of geochemically different material occur within them, complicating any progression in till lithology. In general, therefore, although changes in till lithology are found upwards in the till sequence at most sites, supporting Boulton's (1996a, b) model, the stacking, folding and attenuation of these units has often complicated the geochemical signature.

In conclusion, this research shows that the geochemical signatures of the eastern England tills do not correspond directly to the traditional Basement, Skipsea and Withernsea tills and therefore indicates that these till types cannot be differentiated definitively by till matrix geochemistry. In addition, whilst particle size analysis does distinguish between the till units to some extent, the relationship is too weak to differentiate between them. This research therefore proposes that the till sequences along the east coast of England were deposited beneath an oscillating ice margin. Changes in till matrix geochemistry relate to changes in the dominance of (possibly surging) ice lobes of potentially different provenance, which not only re-worked pre-existing Quaternary sediments (i.e. from previous glacial advances) and excavated local bedrock (chalk and at Filey limestone) during their advance, but also progressively mixed these sediments with more far travelled material from further north (i.e. limestone, shales and mudstones). Consequently, it is recommended that although the traditional division of the Skipsea and Withernsea tills and their equivalents north and south may still relate to advances and readvances of the Late Devensian North Sea ice lobe in this region, they should no longer be regarded as lithologically distinct till units.

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Appendix i: List of elements

Al - Aluminium
Ag - Silver
As - Arsenic
B - Boron
Ba - Barium
Be - Beryllium
Bi - Bismuth
Ca - Calcium
Cd - Cadmium
Ce - Cerium
Co - Cobalt
Cr - Chromium
Cu - Copper
Fe - Iron
Ga - Gallium
K - Potassium
Li - Lithium
Mg - Magnesium
Na - Sodium
Nb - Niobium
Nd - Neodymium
Ni - Nickel
Ti - Titanium
P - Phosphorus
Pb - Lead
Rb - Rubidium
Sb - Antimony
Se - Selenium
Si - Silicon
Sn - Tin
Sr - Strontium
Th - Thorium
Tl - Thalium
V - Vanadium
U - Uranium
Y - Yttrium
Zr - Zircon
Zn - Zinc

Appendix ii: Bar and line graphs of element abundances by sample and by height

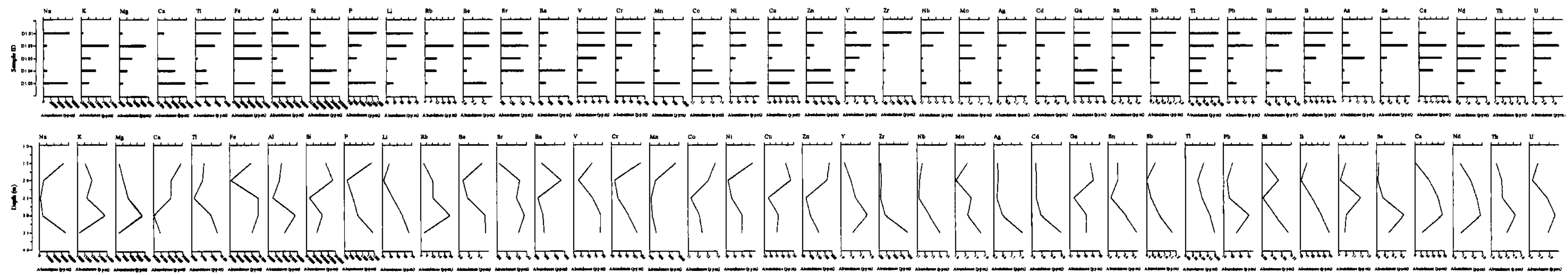


Figure A1. Element abundances in samples from Site 1 Dimlington. Upper: by sample. Lower: by height.

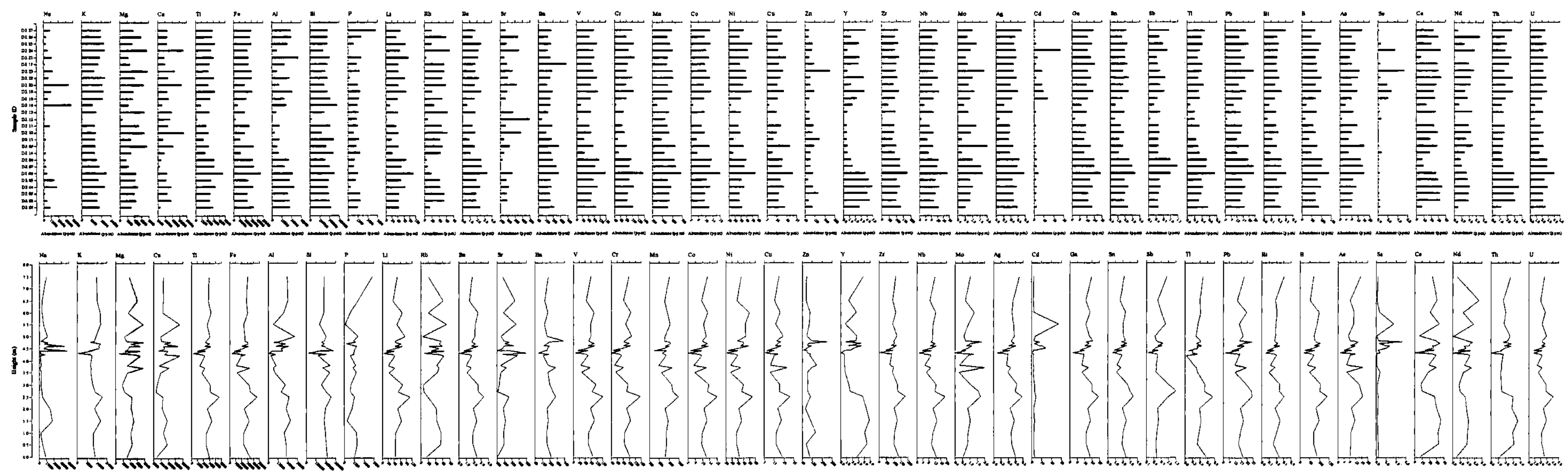


Figure A2. Element abundances in samples from Site 2 Dimlington. Upper: by sample. Lower: by height.

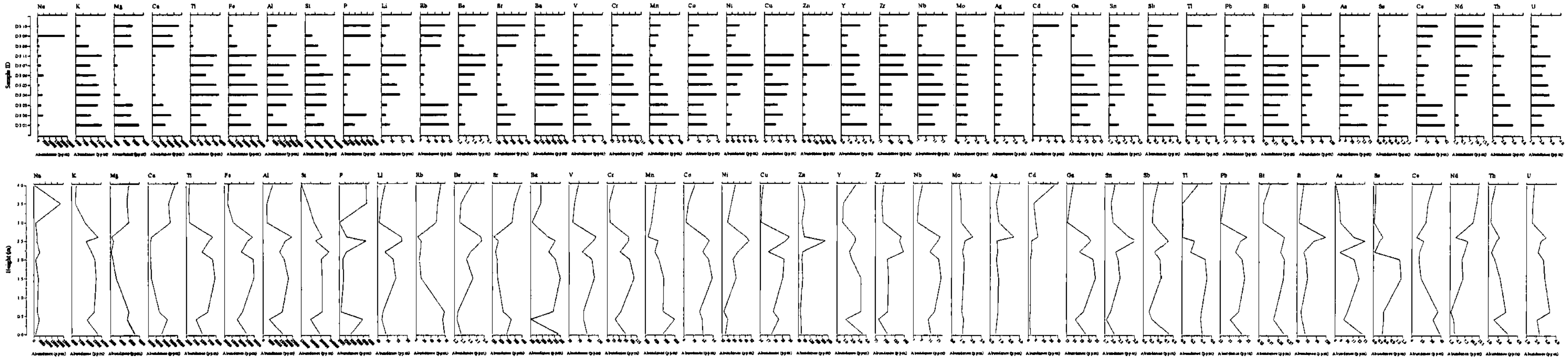


Figure A3. Element abundances in samples from Site 3 Dimlington. Upper: by sample. Lower: by height.

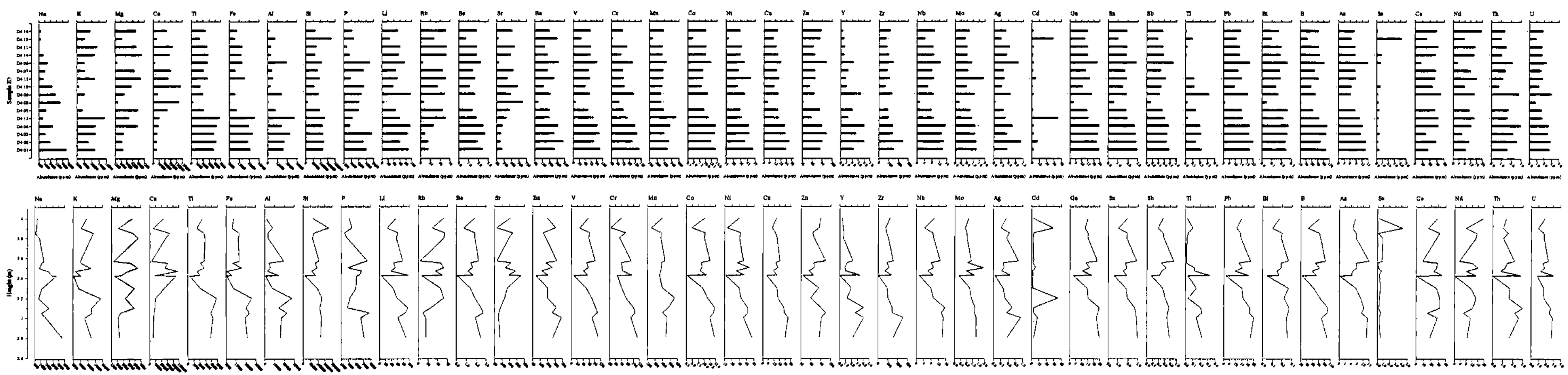


Figure A4. Element abundances in samples from Site 4 Dimlington. Upper: by sample. Lower: by height.

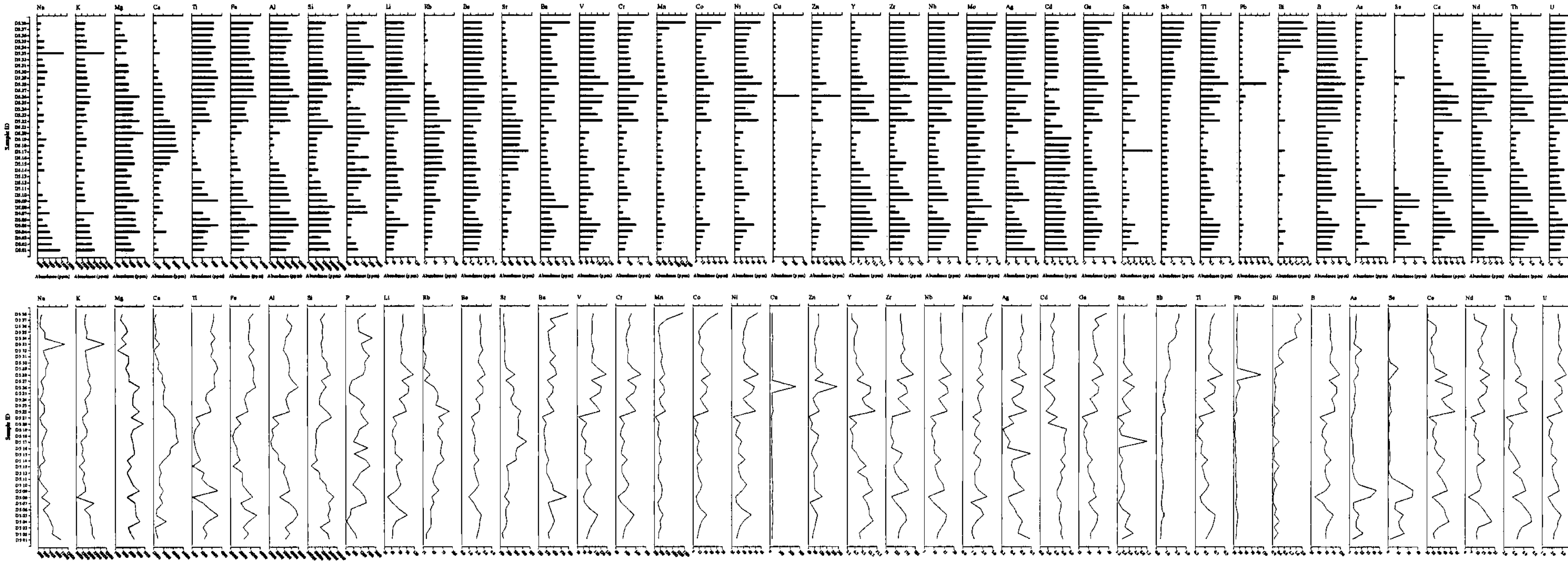


Figure A5. Element abundances in samples from Site 5 Dimlington. Upper: by sample. Lower: by height.

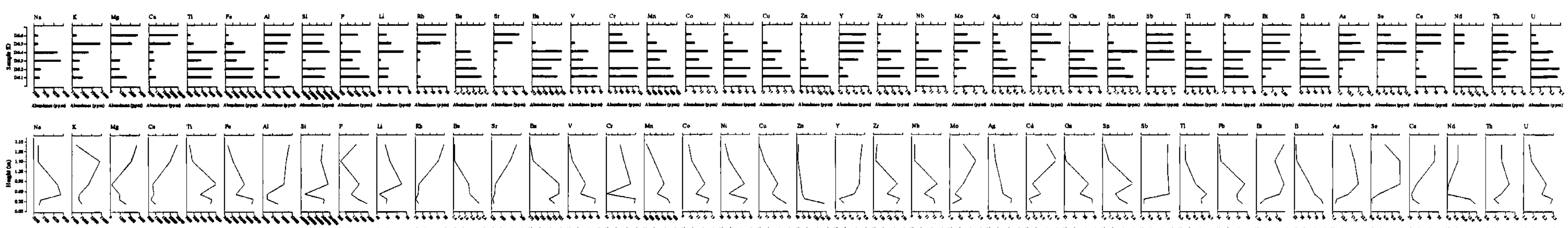


Figure A6. Element abundances in samples from Site 6 Dimlington. Upper: by sample. Lower: by height.

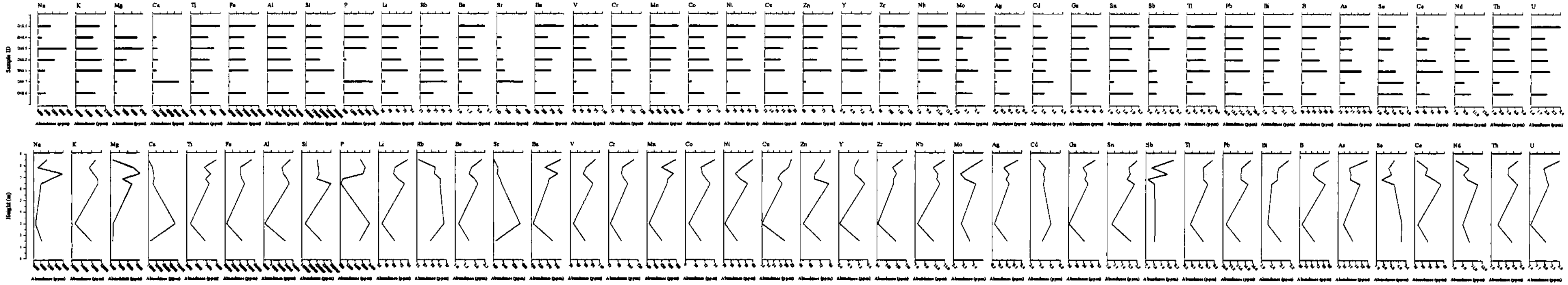


Figure A7. Element abundances in samples from Site 10 Dimlington. Upper: by sample. Lower: by height.

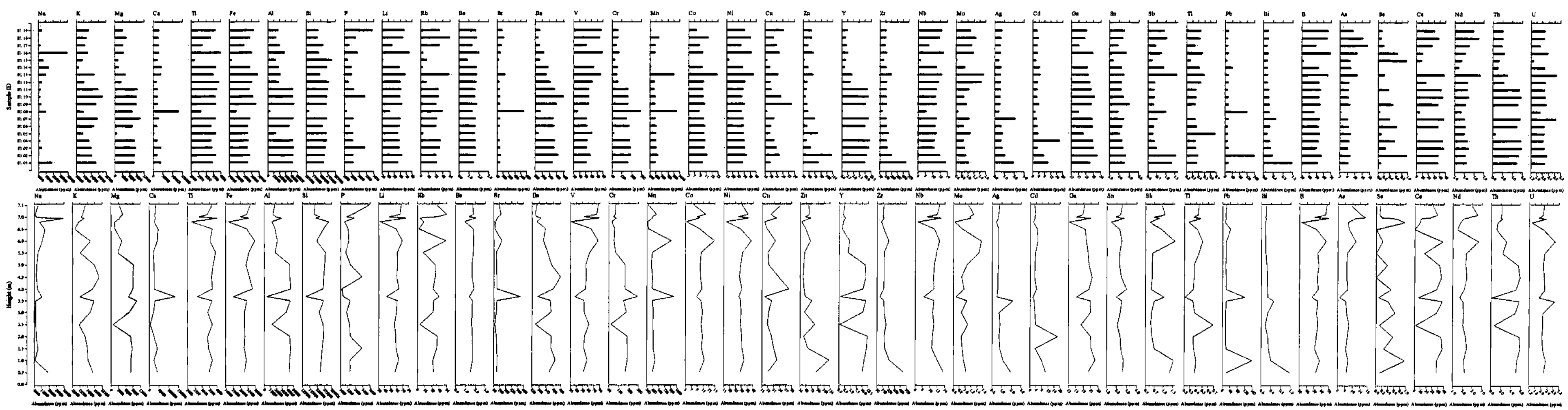


Figure A8. Element abundances in samples from Site 1 Skipsea. Upper: by sample. Lower: by height.

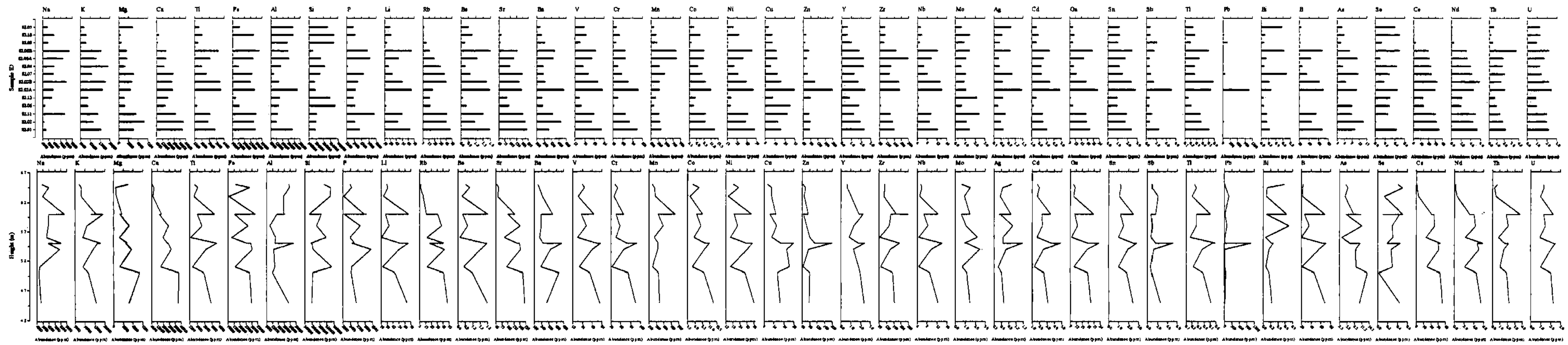


Figure A9. Element abundances in samples from Site 2 Skipsea. Upper: by sample. Lower: by height.

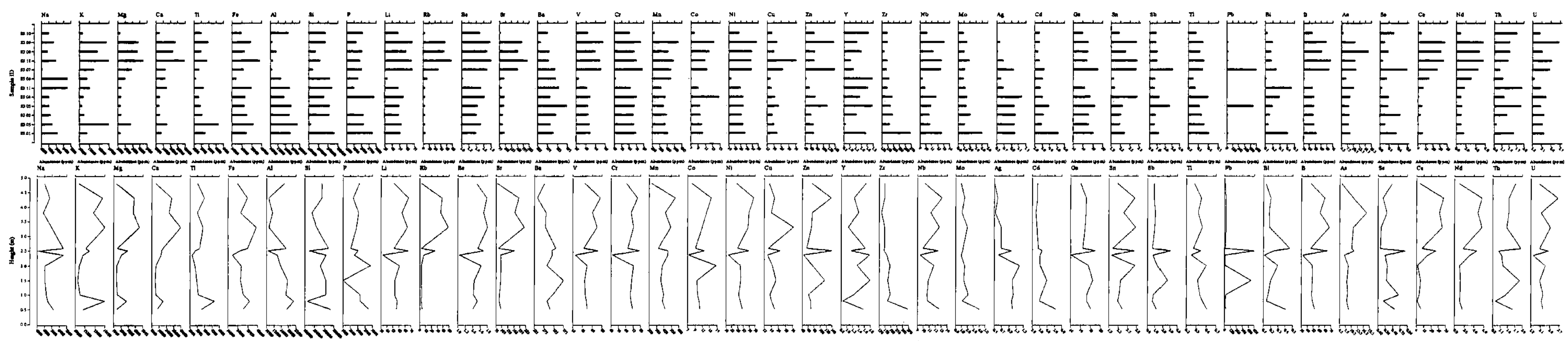


Figure A10. Element abundances in samples from Site 3 Skipsea. Upper: by sample. Lower: by height.

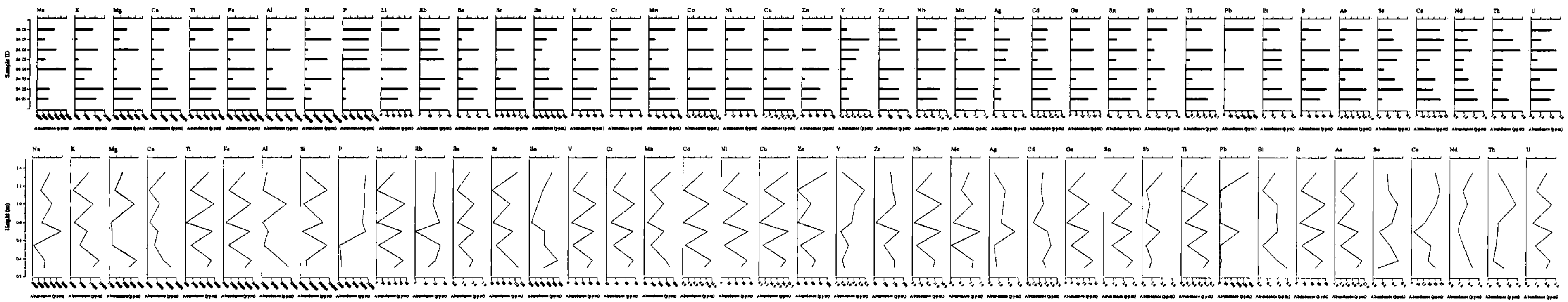


Figure A11. Element abundances in samples from Site 4 Skipsea. Upper: by sample. Lower: by height.

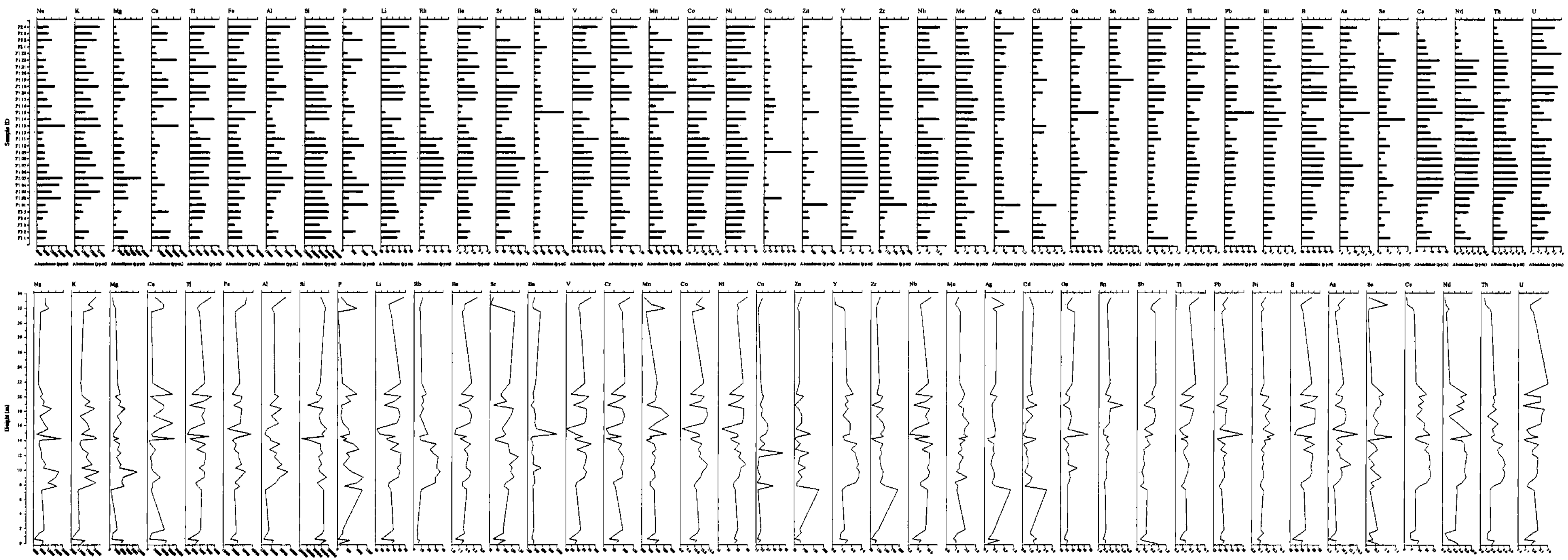


Figure A12. Element abundances in samples from all sites at Filey. Upper: by sample. Lower: by height.

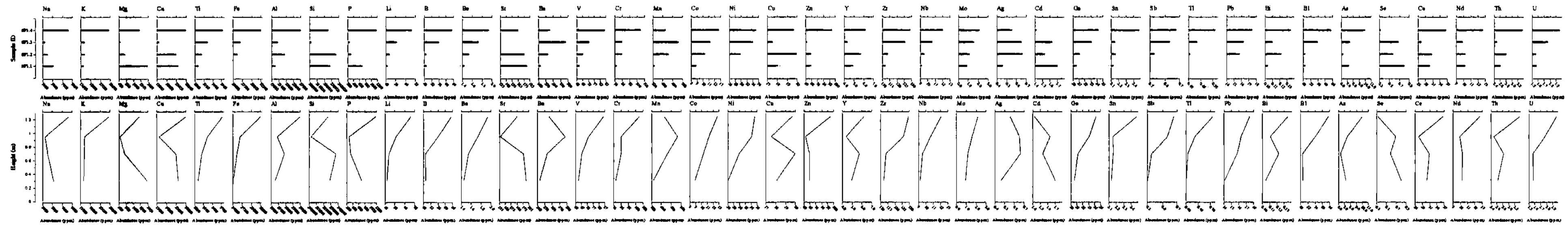


Figure A13. Element abundances in samples from Site 1 South Ferriby. Upper: by sample. Lower: by height.

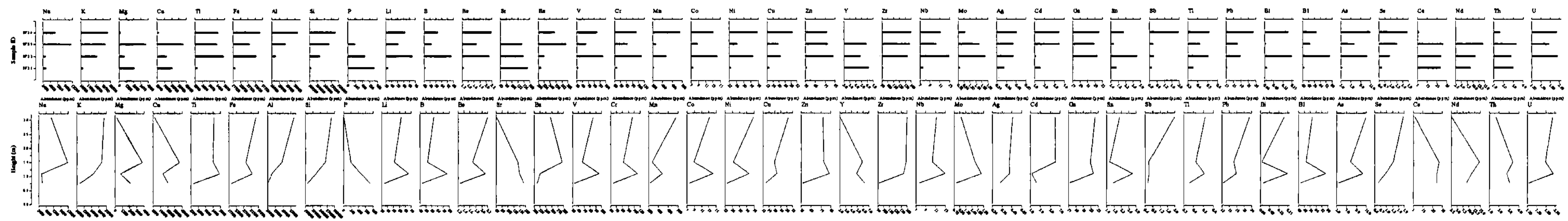


Figure A14. Element abundances in samples from Site 2 South Ferriby. Upper: by sample. Lower: by height.

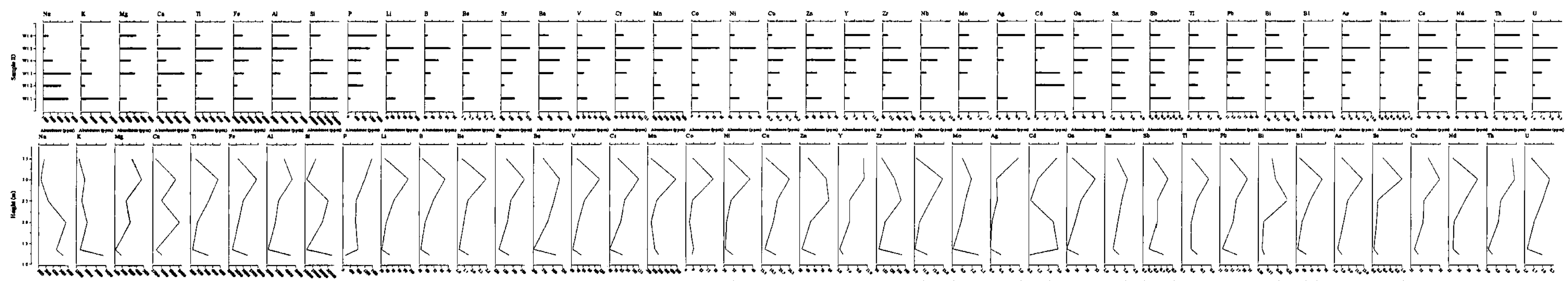


Figure A15. Element abundances in samples from Welton-Le-Wold. Upper: by sample. Lower: by height.

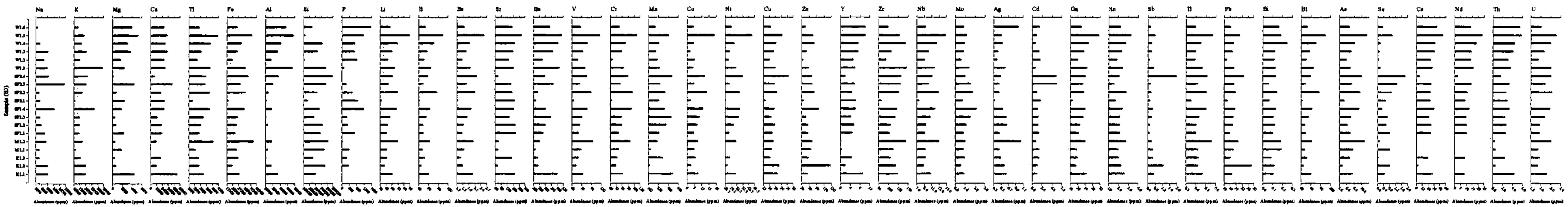


Figure A16. Element abundances in samples from South Ferriby, Welton-Le-Wold, Kirmington and Morston. Upper: by sample. Lower: by height.

Appendix iii: Cluster Dendrograms which include sand, clay and gravel samples

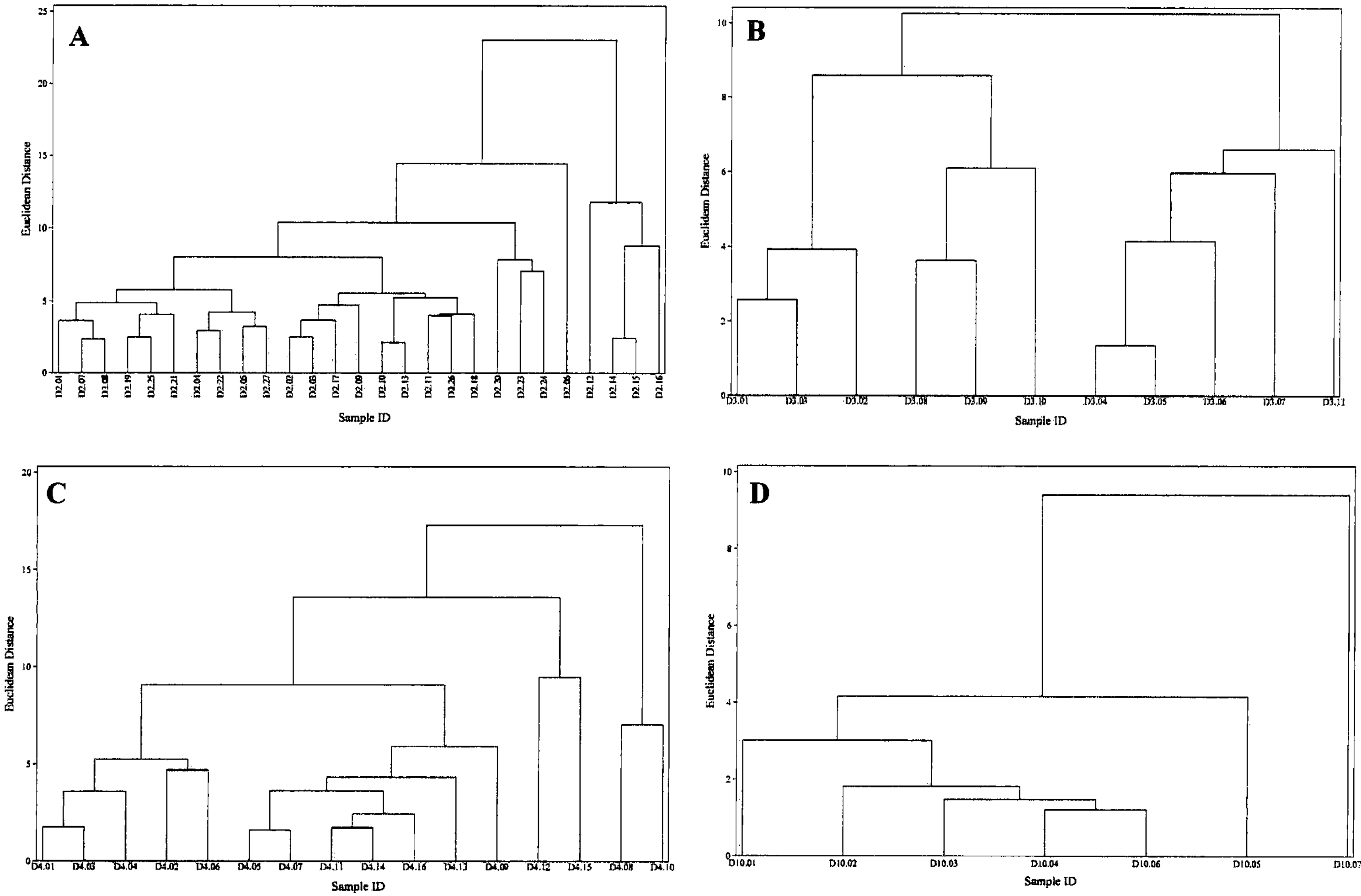
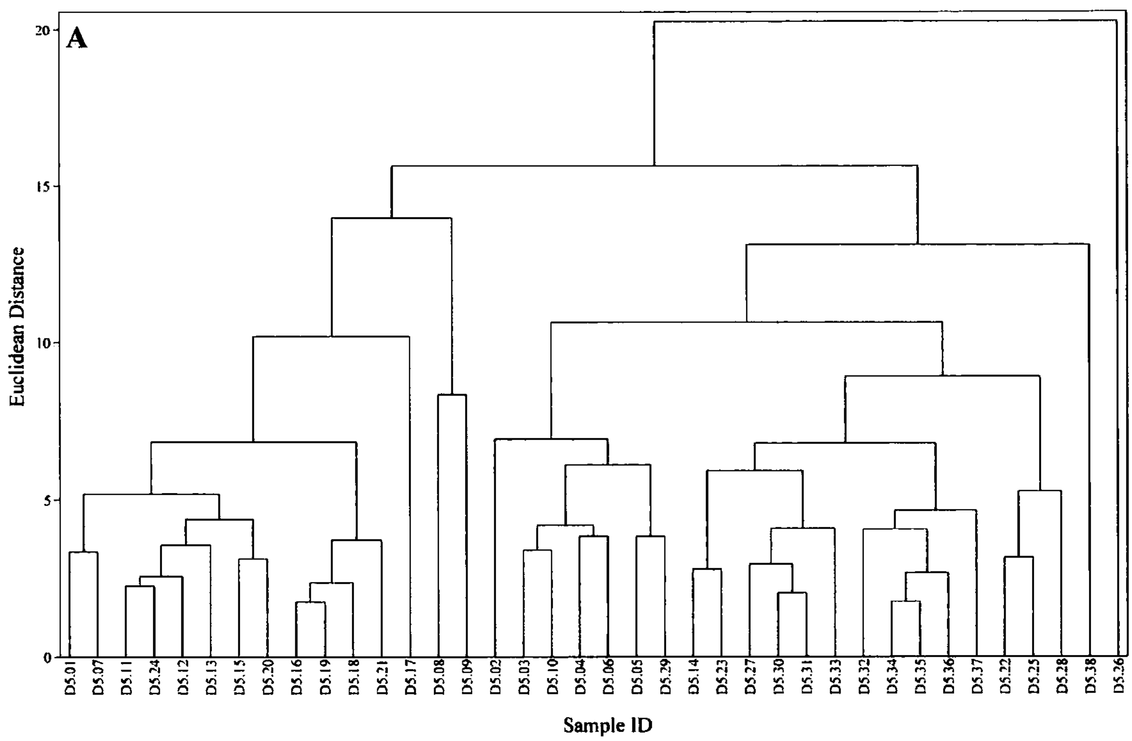


Figure A17. Dimlington, dendrograms of cluster analysis using complete linkage, combined z-scores at A) Site 2, B) Site 3, C) Site 4 D) Site 10.



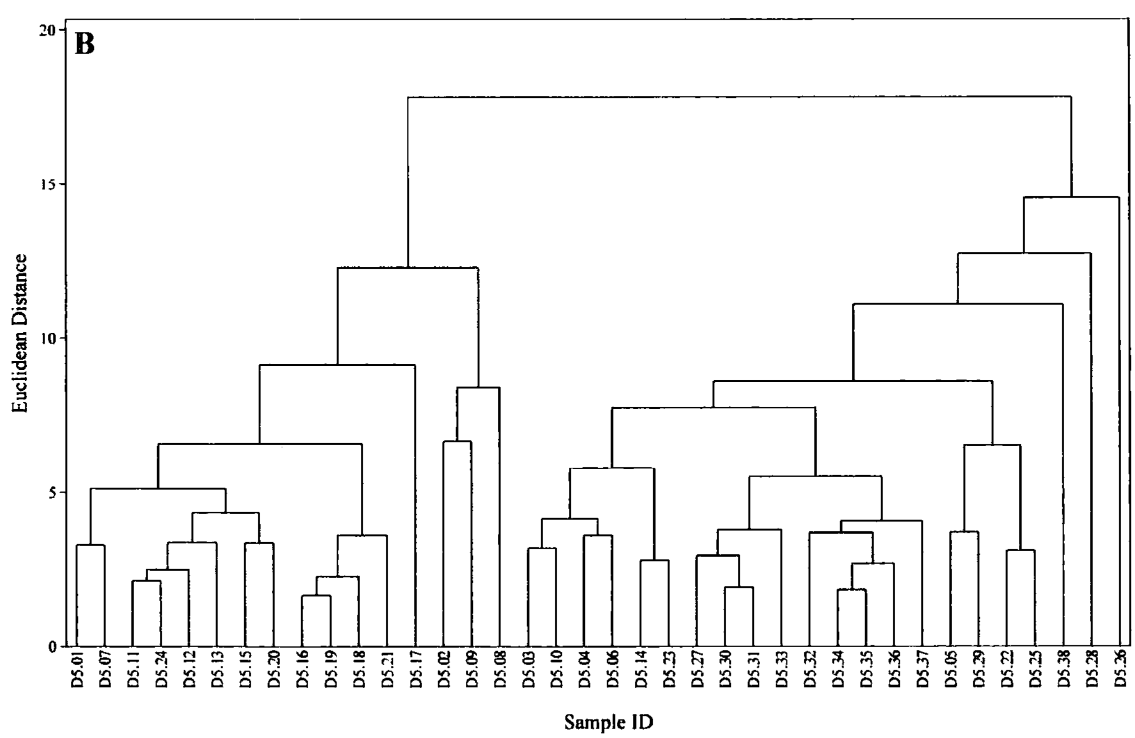


Figure A18. Dimlington Site 5, dendrograms of cluster analysis using complete linkage A) combined z-scores, B) individual z-scores.

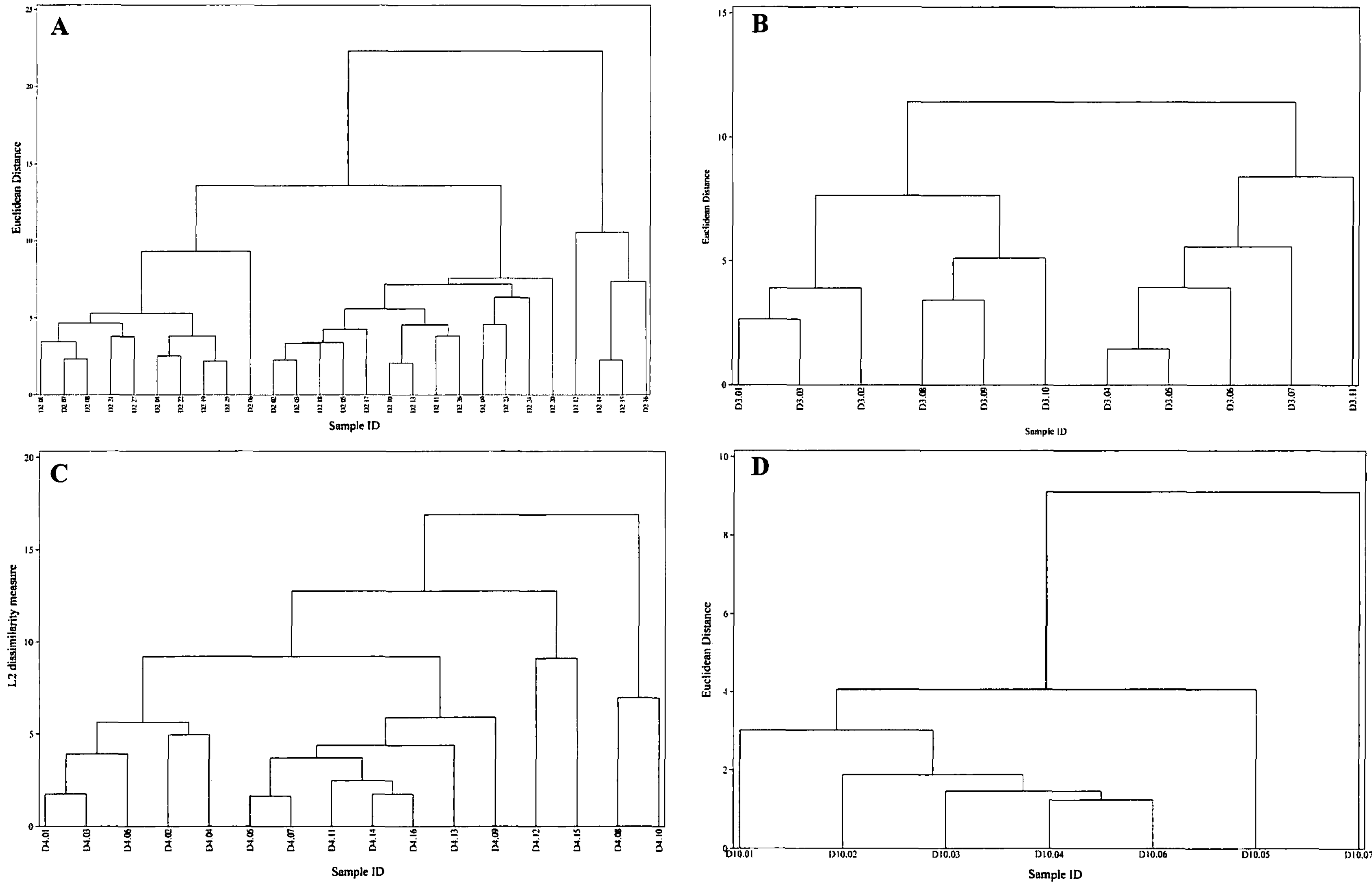


Figure A19. Dimlington, dendrograms of cluster analysis using complete linkage, individual z-scores at A) Site 2, B) Site 3, C) Site 4 D) Site 10.

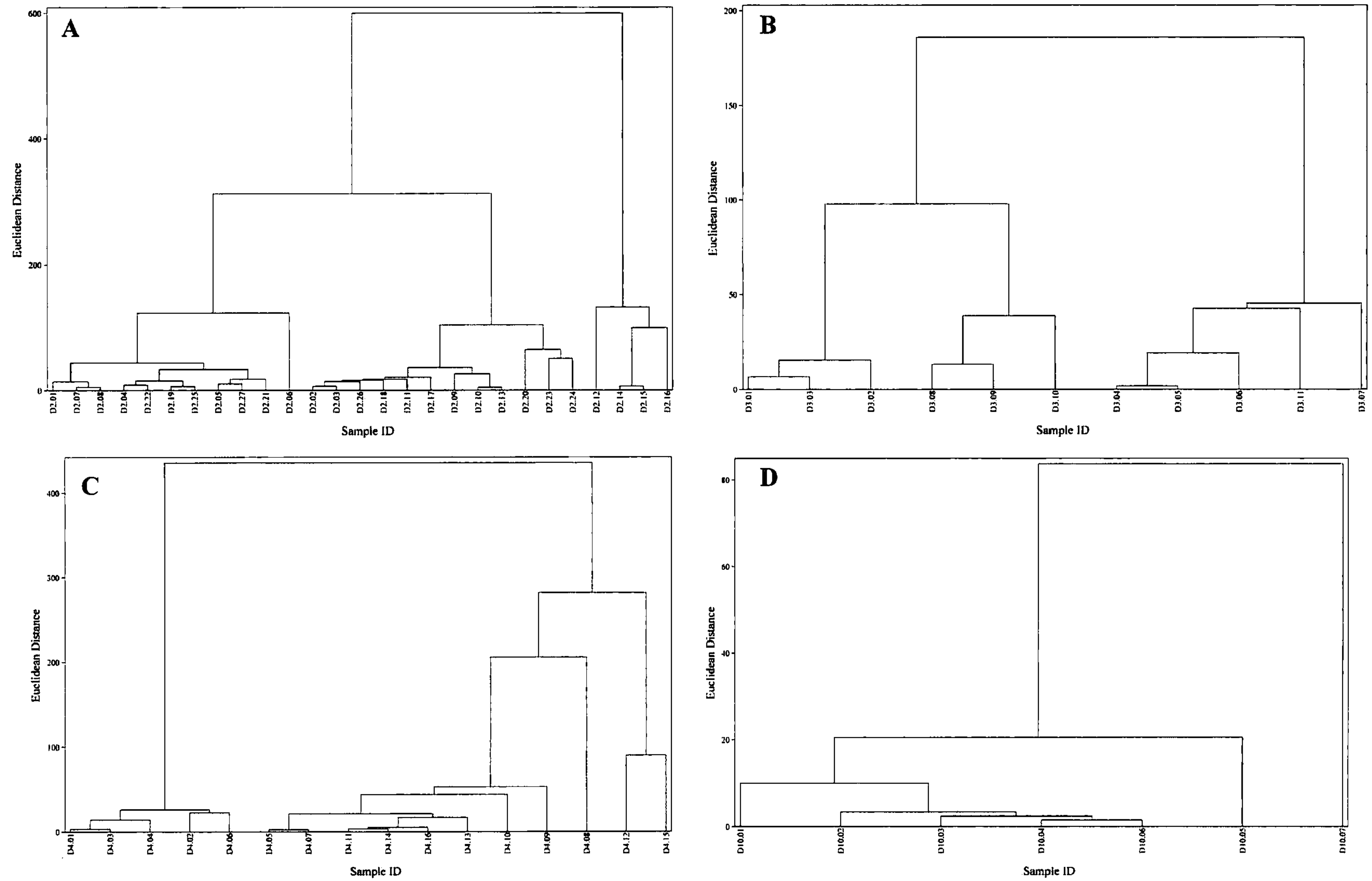


Figure A20. Dimlington, dendrograms of cluster analysis using Ward's method, combined z-scores at A) Site 2, B) Site 3, C) Site 4 D) Site 10.

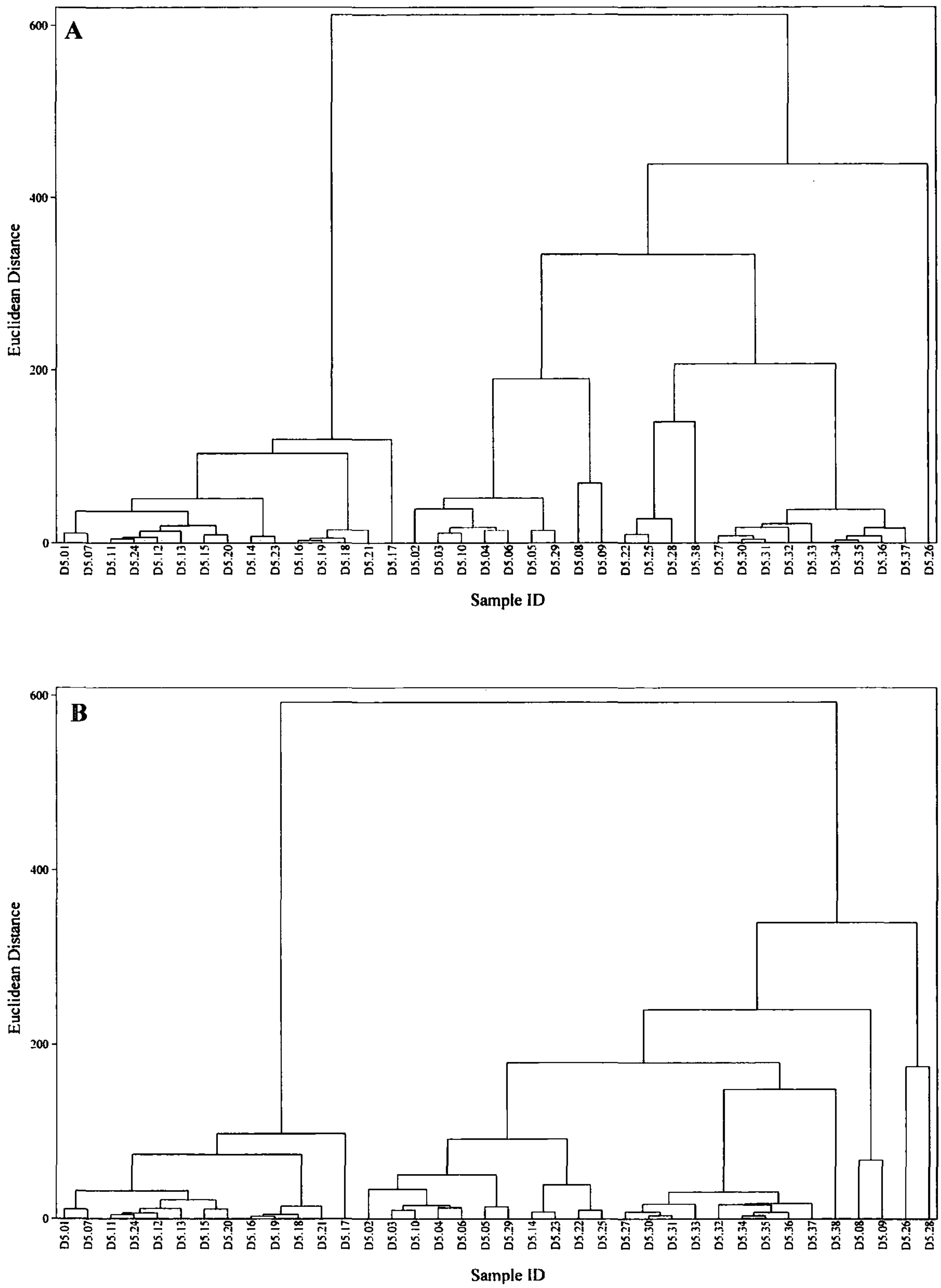


Figure A21. Dimlington Site 5, dendrograms of cluster analysis using Ward's method A) combined z-scores, B) individual z-scores.

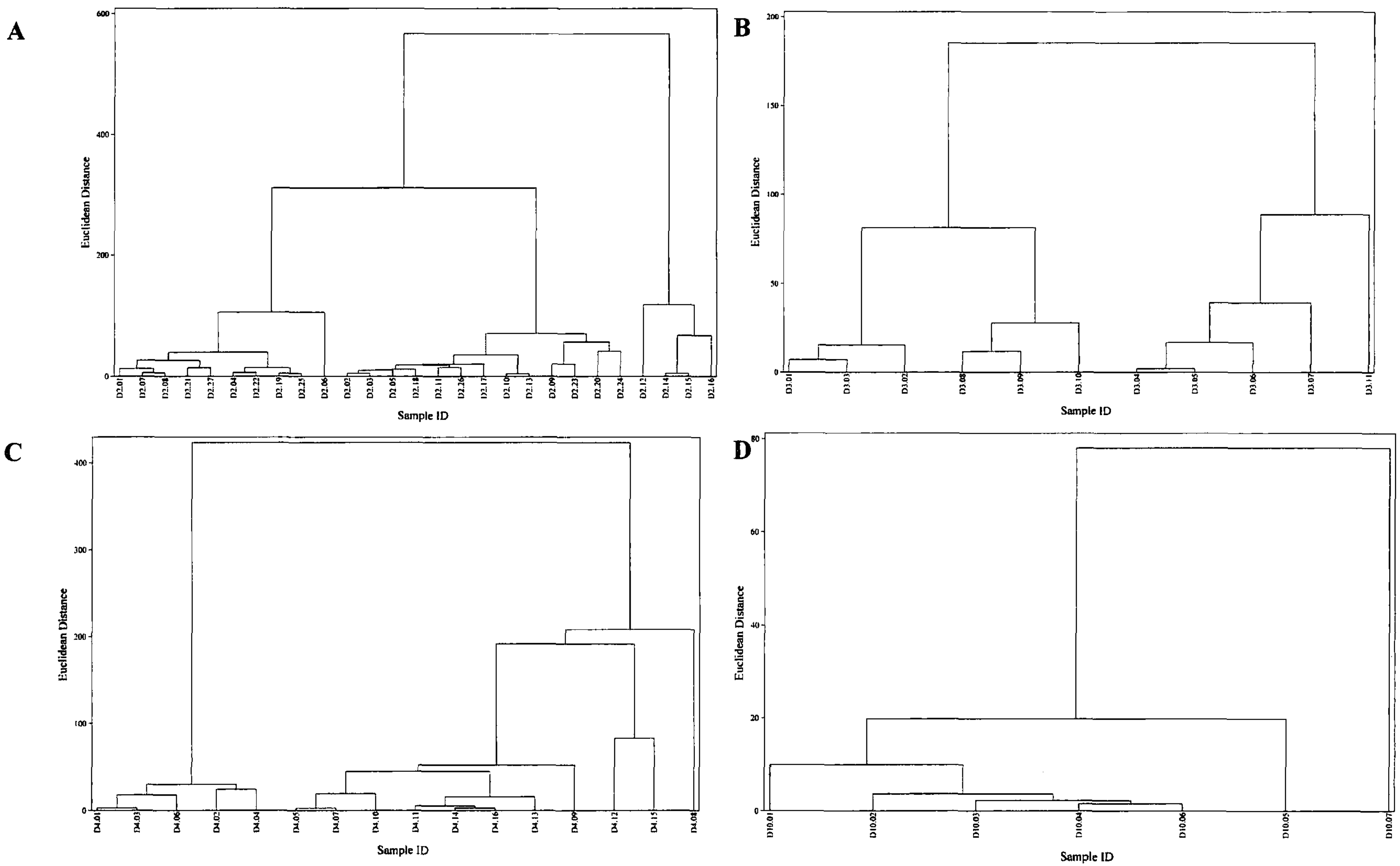


Figure A22. Dimlington, dendrograms of cluster analysis using Ward's method, individual z-scores at A) Site 2, B) Site 3, C) Site 4 D) Site 10.

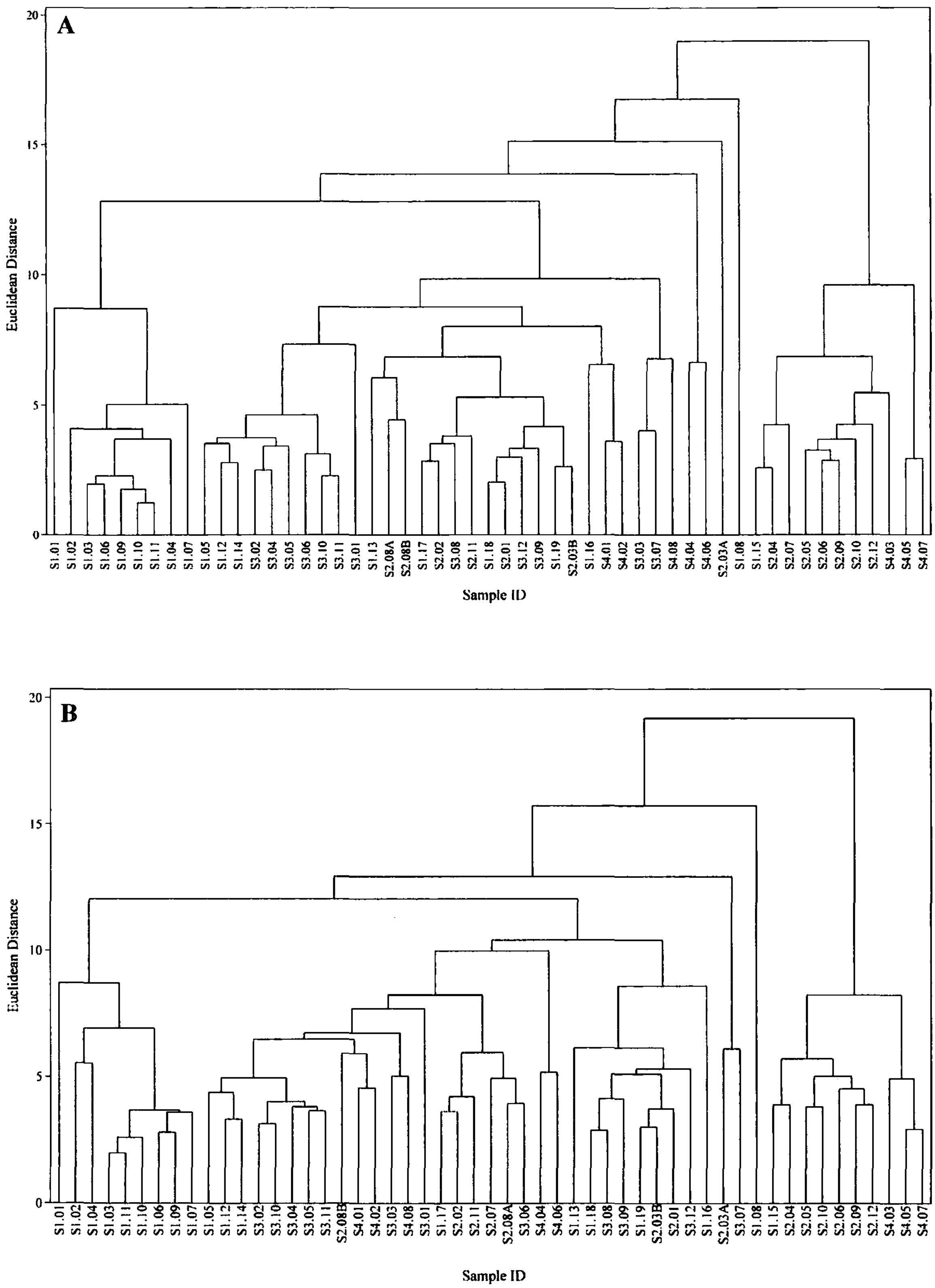


Figure A23. Skipsea, dendrograms of cluster analysis using complete linkage A) combined z - scores, B) individual z-scores.

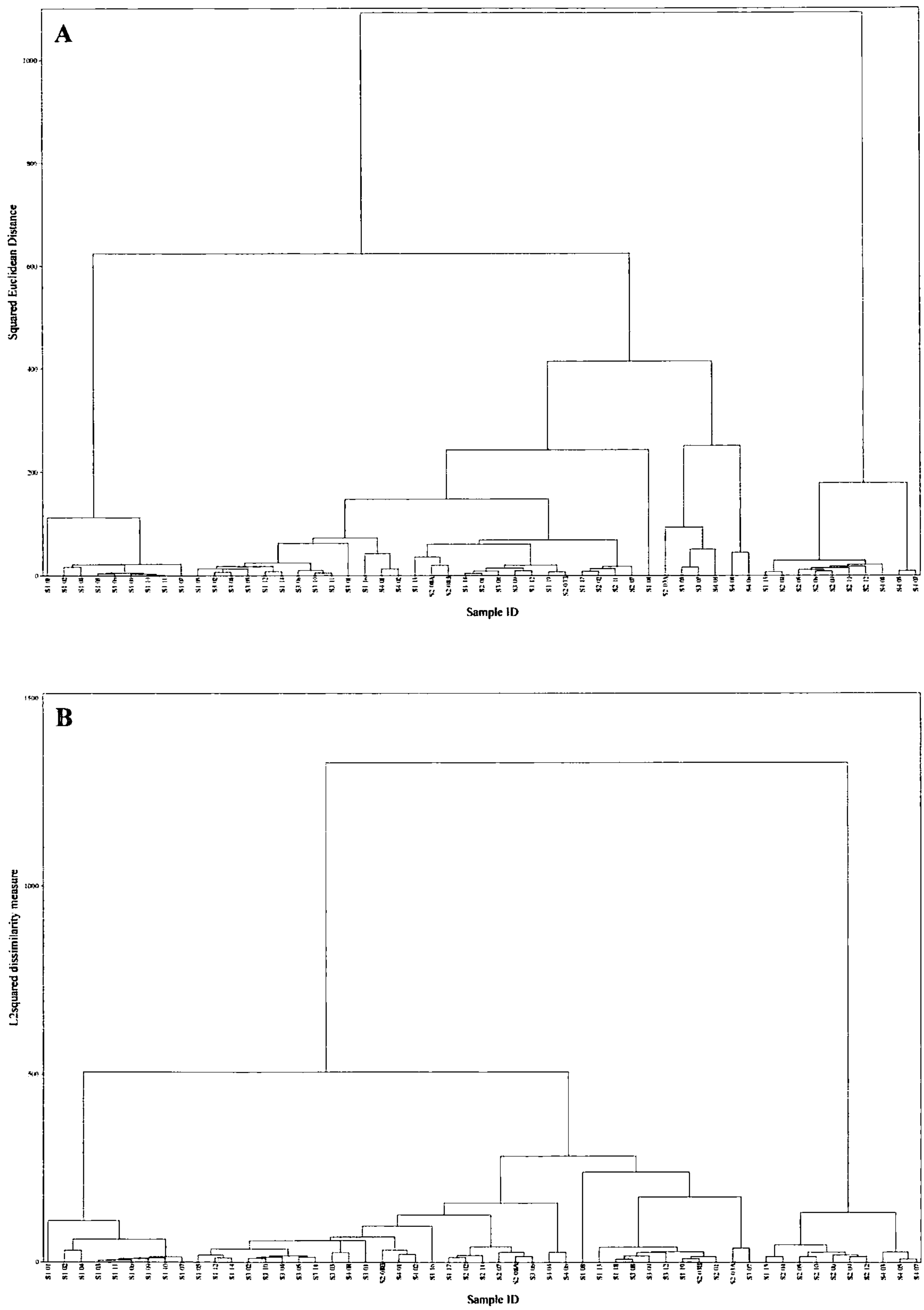


Figure A24. Skipsea, dendrograms of cluster analysis using Ward's method A) combined z - scores, B) individual z-scores.

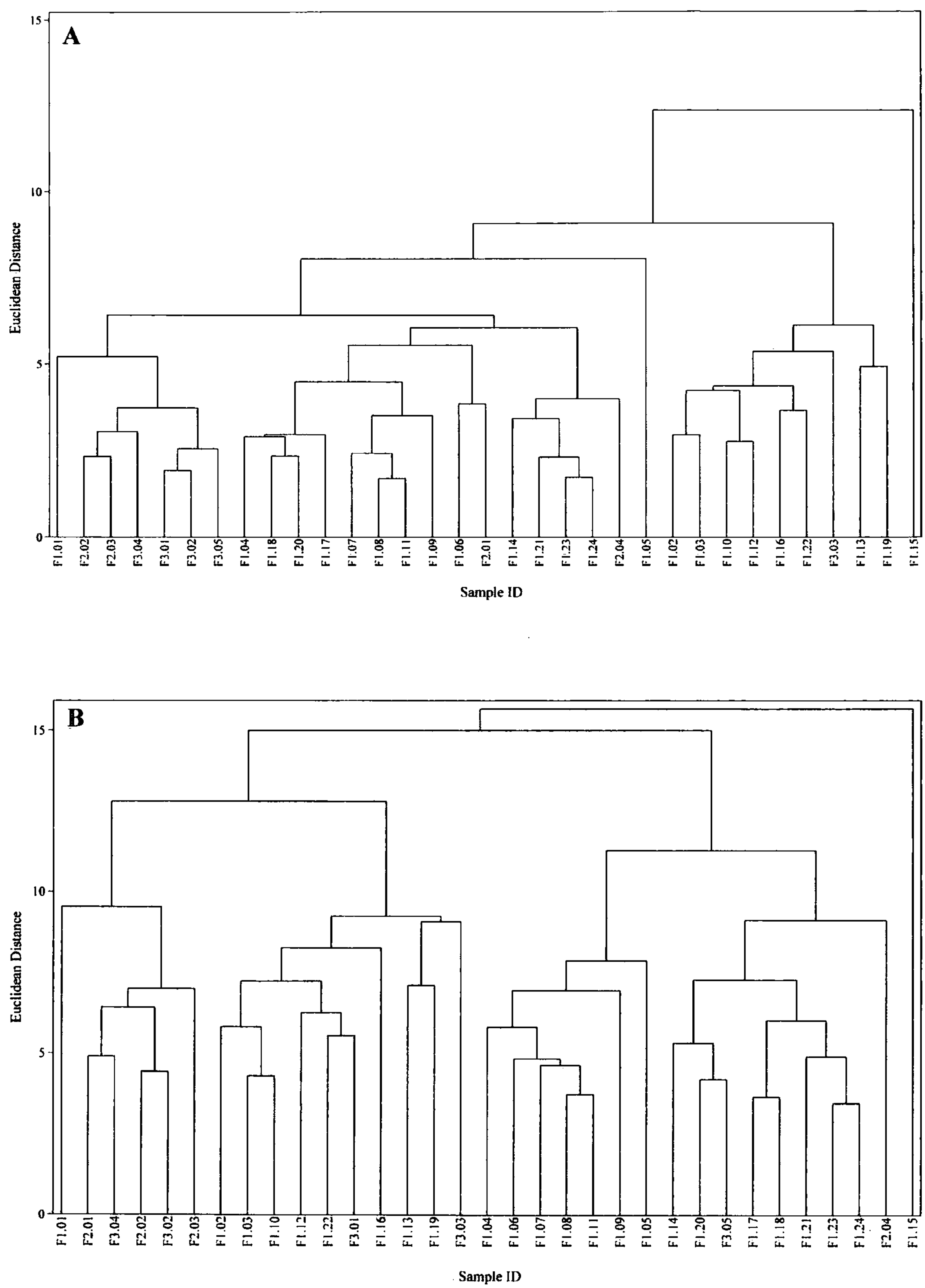


Figure A25. Filey, dendrograms of cluster analysis using complete linkage A) combined z - scores, B) individual z-scores.

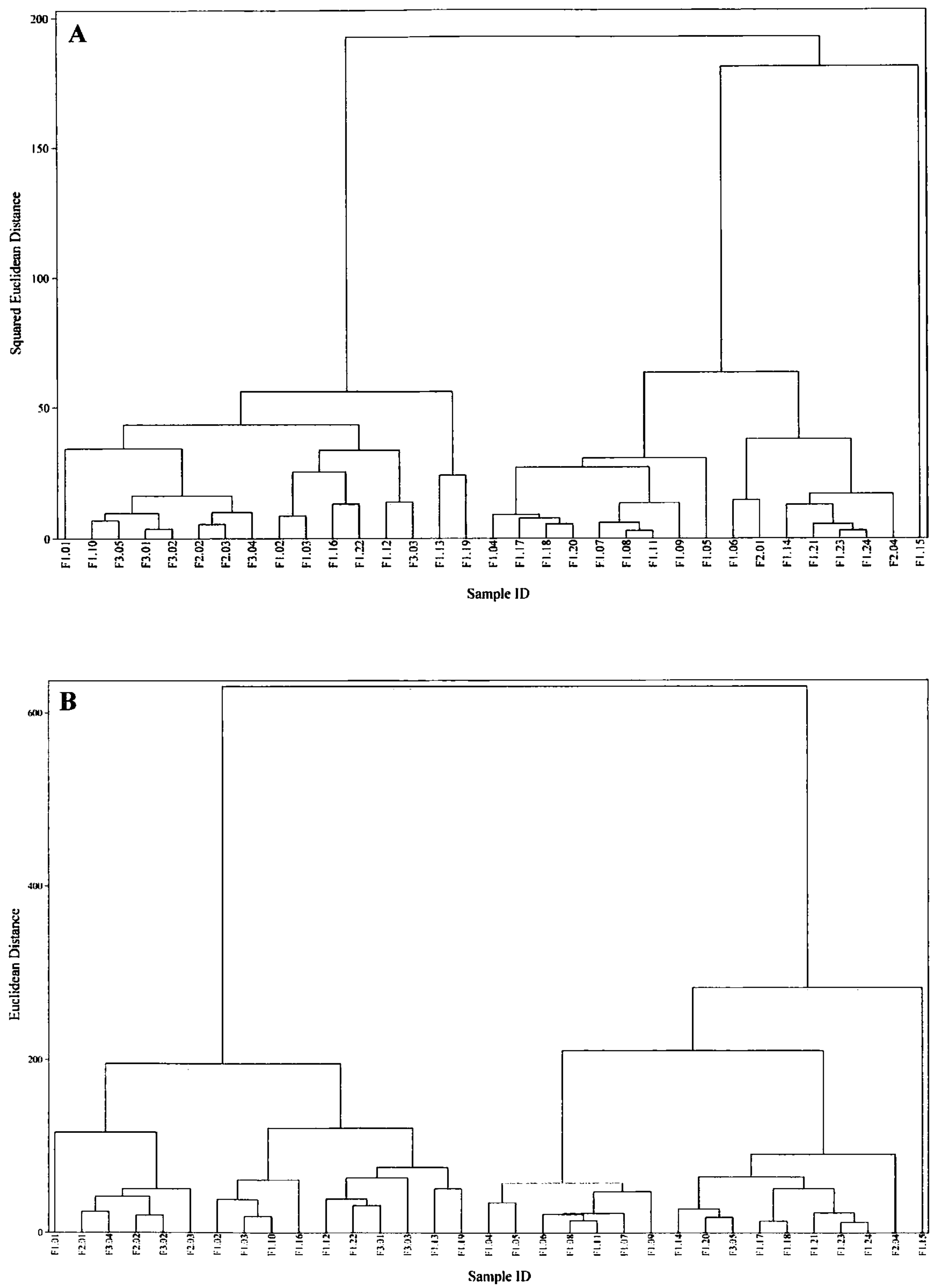


Figure A26. Filey, dendrograms of cluster analysis using Ward's method A) combined z - scores, B) individual z-scores.